Development and Assessment of Engineering Design Competencies using Technology-Enhanced-Learning Environment

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by

Madhuri Mavinkurve

Roll no: 10438803

Supervisor:

Sahana Murthy (IIT Bombay)

Inter-Disciplinary Program in Educational Technology

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Dedication Sheet

Dedicated

To

My husband Mr.K.S.Mavinkurve, my teachers and Almighty

Approval Sheet

Abstract

Engineering is a practice-driven profession. Engineering graduates should be able to demonstrate and apply thinking skills in addition to their domain knowledge. Engineering design thinking skill is one such important thinking skill. Even though this skill is being taught using various instructional methods such as project based learning, it is reported that students are unable to demonstrate engineering design thinking skill. A key challenge is in defining what to teach as engineering design thinking, and how to assess this skill.

In this thesis, we address the problem of developing and assessing engineering design thinking skill among undergraduates. In our solution approach, we operationalized engineering design thinking skill in terms of measurable competencies. We identified the following engineering design competencies: Structure Open Problem, Multiple Representation, Information Gathering, Convergent Thinking and Divergent Thinking. We developed rubrics as a formative assessment instrument for these competencies. The rubrics assess students' progress of competency acquisition as well as provide constructive feedback to attain competency in a given design task.

To help students attain the engineering design competencies, we designed TELE-EDesC - Technology Enhanced Learning Environment for Engineering Design Competency. TELE-EDesC is a self-learning environment which includes interactive learning activities, referred to as 'Learning Dialogs'. TELE-EDesC Learning Dialogs harness the affordances of modern technology such as interactive experimentation, self-regulation, and personalized feedback, to trigger essential metacognitive processes required for engineering design thinking.

We developed TELE-EDesC learning modules for Structure Open Problem (SOP) competency for topics in analog electronics, and tested them using quasi-experimental studies (N=295) as well as qualitative interaction analysis, with second year engineering students. We found that TELE-EDesC was effective for learners in attaining SOP competency (statistically significant differences, $p<0.01$). From the interaction analysis, we identified productive learning behaviours of successful students and revised TELE-EDesC to promote such behaviour among all learners.

The main contributions of this thesis are: TELE-EDesC learning modules that have been empirically validated for SOP competency for a range of topics in analog electronics, a pedagogical framework to develop TEL environments for engineering design competencies, and assessment rubrics for engineering design competencies.

Key words: *Engineering Design Competencies, Rubrics, Structure Open Problem, Technology Enhanced Learning Environment, TELE-EDesC, Learning Dialogs, Pedagogical framework*

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Abbreviation Notation and Nomenclature

ABET	Accreditation Board for Engineering and Technology, Inc.
CANM	Controlled animations
CCQ	Concept Clarification Question
CDIO	Conceive, Design, Implement and Operate
CONV	Convergent thinking
DIV	Divergent thinking
DMTQ	Decision Making Task Question
EDR	Educational Design Research
ICE	Idea Connection Extension
ICT	Information and Communication Technology
IG	Information Gathering
MR	Multiple Representations
PBL	Problem Based Learning
SM	Simulative Manipulation
SOP	Structure Open Problem
TEL	Technology enhanced learning
TELE-EDesC	Technology Environment to develop engineering design competencies
TIDEE	Team Design Skill Growth Survey

Declaration Sheet

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute/the Academy and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

(Signature)

Mrs.Madhuri Krishnanand Mavinkurve

(Name of the student)

10438803

(Roll No.)

Date:

Chapter 1

Introduction

Engineering is a practice profession. Thus, in addition to content knowledge in various topics, engineering students should be able to demonstrate and apply various cognitive or thinking skills such as problem formulation and problem solving, designing and conducting experiments, data analysis and interpretation, design of systems to meet needs and constraints, modelling real-world systems processes, and so on. (Besterfield-Sacre et al., 2000; Shuman et al., 2005). Thinking skills are cognitive processes that human beings apply for sense-making and problem-solving (Beyer, 1988). One such important cognitive or thinking skill for engineering education is engineering design thinking skill (Atman et al., 1999; Dym, 2005). It has been recommended that graduates of engineering programs should be those who can design effective solutions to meet social needs (ABET 2012). In addition, a fundamental objective in undergraduate engineering laboratories is, "Design, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials; developing system specifications from requirements; and testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements" (Dym, 2005).

As an example, consider a scenario wherein electronics companies manufacture a wide variety of testing equipment. The company hires fresh electronics engineering graduates who are assigned the responsibility of designing a function generator, which is an instrument that produces variety of test signals. In order to design a function generator, the engineer should be aware of its purpose, the waveforms that need to be designed, the amplitude and frequency ranges to be provided and other such requirements. He/she is expected to identify which circuits and block diagrams will satisfy the requirements. The set of thinking skills required to design solutions to such type of problems is the context of this thesis and referred as "engineering design thinking skill".

Engineering design thinking skill is a combination of complex cognitive process such as ill-structured problem solving, inquiry learning and systematic decision making (Dym, 2005; Aurisicchio et.al, 2007). The complexity of cognitive process makes it difficult to teach and learn skills.

Engineering design is taught in many universities and institutes as a separate course and based on a version of project-based learning (PBL) (Wilczynski & Douglas, 1995; Benjamin & Keenan, 2006). In PBL-based courses, students are given an open-ended problem for which they need to design products, which are then evaluated (Dunn-Rankin et.al., 1998). Some of the design courses were based on reverse engineering (Wood et.al, 2001) methods of product development. Even though these courses have been reported as useful ones, these courses are resource intensive in terms of faculty time, infrastructure and cost. These courses are project or problem oriented than design thinking skill development.

The above problem is compounded in part because of the lack of a unique definition of what comprises engineering design thinking. Engineering design thinking is perceived in different ways by educationists and researchers. Some consider engineering design thinking as critical steps (Aurisicchio et.al., 2007) to be followed, some perceive it as a problem solving activity (Pahl et al.,1996; Ullman,1988; Gero, 1990), and some consider it as developing competencies (Plonka et.al., 1994).

Another reported challenge in the teaching-learning of engineering design thinking skill is the assessment of students' performance in engineering design courses (Dutson et. al., 1997). Engineering design is an ill-structured, open-ended task. Varied assessment methods are possible and different assessment instruments exist, however there is no standard process or instrument.

1.1. Problem statement

The broad problem addressed in this thesis is that of teaching engineering design thinking, which has reported challenges in its teaching and assessment. One approach to address the above challenges of developing as well as assessing complex thinking skills is that of identifying measurable competencies associated with the thinking skill (for example, the competencies defined by ABET for engineering undergraduates (ABET 2000). In this thesis, we take this approach and consider engineering design thinking skill in terms of competencies. Some researchers have taken this approach (Plonka et al., 1994; Crain et al., 1995), but different researchers have addressed the competencies using different terminologies.

To define the specific problem for this thesis, we reviewed existing research to identify engineering design competencies, analysed and mapped the common competencies and synthesized them into a set of competencies which can then form the basis of developing teaching-learning solutions and assessment instruments. The important competencies required for engineering design thinking that emerged from the literature review are: Structure Open Problem (SOP), Multiple Representations (MR), Information Gathering (IG), Divergent thinking (DIV) and Convergent thinking (CONV).

This led to the central research issue addressed by the thesis, i.e. the teaching-learning and assessment of engineering design competencies. The main research question is:

How to develop and assess engineering design competencies?'

1.2. Solution overview

1.2.1. Motivation for solution

Learning of thinking skills such as design requires complex learning environments (Hmelo-Silver et al., 2004; Linn, Clark & Slotta, 2003). One approach to developing such learning environments is by harnessing the affordance of modern technology (Reiser, 2004). In recent years, the affordances of ICT have led to the development of technology enhanced learning (TEL) environments to teach various thinking skills. These TEL environments contain affordances such as interactive experimentation (van Joolingen et al., 2005), self-regulation (Azevedo et al., 2010; Molenaar & Roda, 2011), personalized feedback (Reiser, 2004) that provide opportunity to students to perform the required complex cognitive tasks. TEL environments are self-learning and work as supportive training material which will reduce faculty load in design courses.

There exist numerous TEL systems to promote various thinking skills in learners such as modelling ability, scientific reasoning and inquiry skills, argumentation, and virtual experimentation. Notable ones include WISE (Linn et. al. 2003), Co-Lab (van Joolingen et. al., 2005), numerous ones on scientific argumentation (Scheuer et. al, 2010 contains many examples) and Go-Lab (de Jong et al., 2014). Most of these TEL environments focus on middle school and high school levels with fewer for tertiary education, and none explicitly address engineering design thinking skill.

1.2.2. TELE-EDesC: TEL Environment for Engineering Design Competencies

We developed 'TELE-EDesC' (pronounced as "Tele-desk") - a Technology Enhanced Learning Environment to teach Engineering design Competencies. TELE-EDesC contains learning modules with interactive learning actions and activities to be performed by the learner. These are referred as Learning Dialogs.

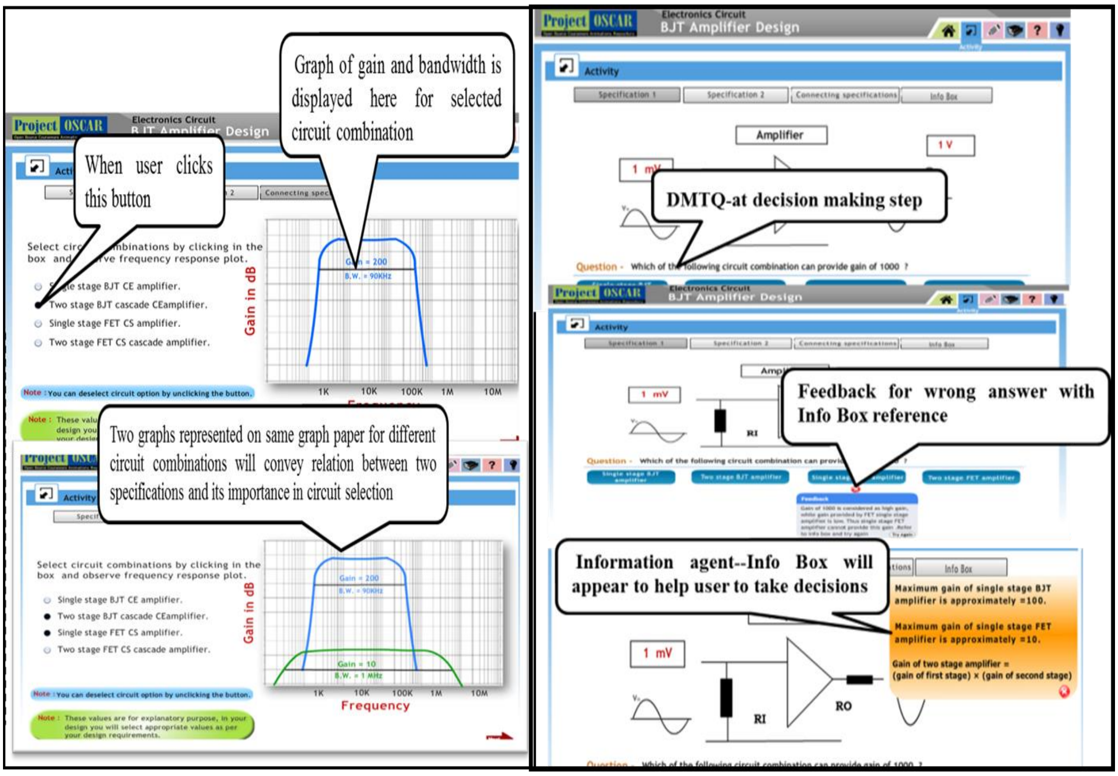


Fig. 1.1. Learning Dialogs of TELE-EDesC

Fig. 1.1 shows an examples of a TELE-EDesC Learning Dialogs to teach the engineering design competency of Structure Open Problem (SOP).We explained Simulative

Manipulation (left figure of Fig. 1.1) and Decision Making Task Question Learning Dialogs (right figure of Fig. 1.1) of SOP. In the Simulative Manipulation Learning Dialog shown in the example, learners are provided with control to vary different parameters and explore the variations. In Decision Making Task Questions (DMTQ), guided questions, are provided to reflect on design effectiveness of variations. The call-outs in the figure show components of Learning Dialogs such as graphs, feedback boxes, information box and its role in learning. TELE-EDesC contains variety of such Learning Dialogs to address various engineering design competencies.

In order to assess learners' engineering design competencies, we developed assessment rubrics. Rubrics are descriptive rating scales which consist of pre-established performance criteria to evaluate student's performance or product resulting from performance task (Mertler, 2001). Rubrics have been suggested as a suitable instrument to evaluate open ended activities (Bailey & Szabo, 2007) like design. Rubrics are known for their capacity to enhance deep learning amongst students by providing rich, detailed and specific feedback to students about their performance. Rubrics contain criteria to achieve the competency, target scoring description and intermediate level scoring descriptions. This make process of evaluation transparent to learners. Table 1.1 shows example of rubrics to assess one sub-competency of structure open problem competency.

Table 1.1. Rubrics items for Structure Open Problem (SOP) competency

Design sub-competency	**Target performance**	**Needs improvement**	**Inadequate**	**Missing**
Is able to extract required relevant specifications in detail from given open ended problem	All relevant visible and hidden specifications are identified in detail and interpreted accurately. No irrelevant specifications identified.	An attempt is made to identify specification Most of them identified but few hidden ones missing or needs more interpretation.	An attempt is made but most of the identified specifications are are wrong or irrelevant or incomplete.	No attempt is made to extract specifications

1.2.3. Approach to designing solution

The solution is approached using following steps (Fig. 1.2):

- Operationalization of engineering design competencies into smaller measurable units - "sub-competencies".

- Development of the assessment instrument.
- Development of pedagogical framework to design TEL environment, and its application into the TELE-EDesC learning modules.
- Evaluation of TELE-EDesC learning modules in terms of learning effectiveness of design competencies and refinement of modules based on results.
- Extension of TELE-EDesC beyond scope.

These steps are implemented using Education Design Research Method (Van den Akker, 2012) explained in next section 1.3.

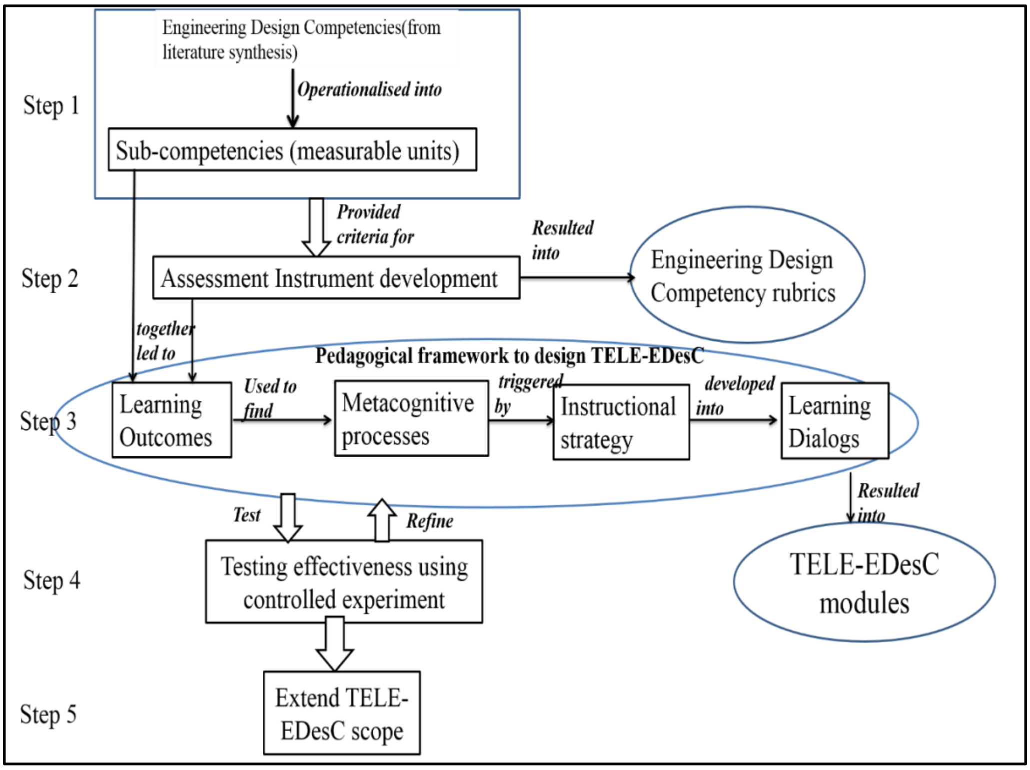


Fig. 1.2. Steps of solution approach

1.3. Methodology

The main research question 'How to develop and assess engineering design competencies?' is answered using Education Design Research (EDR) (Van den Akker, 2012). EDR is "design and development of intervention as a solution to complex educational problem as well as advance knowledge of researchers about the characteristics of intervention.” EDR has four phases as problem analysis, design of prototype, evaluation and refinement. The phases are sequentially executed and the outcomes of each phase triggers the next phase (Fig. 1.3). The detailed EDR method is described in Chapter 3, and a summary of its application is given below.

In the first phase of EDR, the problem analysis phase, engineering design thinking skill is characterised as measurable competencies through analysis and synthesis of literature on this topic. In this phase, we also reviewed various assessment methods and instruments for assessing design competencies. We explored instructional methods to teach thinking skills using TEL environments. The problem analysis provided the specific research questions of the thesis as

1) *How to assess engineering design competencies?*
2) *How to develop TEL environment to teach engineering design competencies?*

This phase is described in Chapter 2.

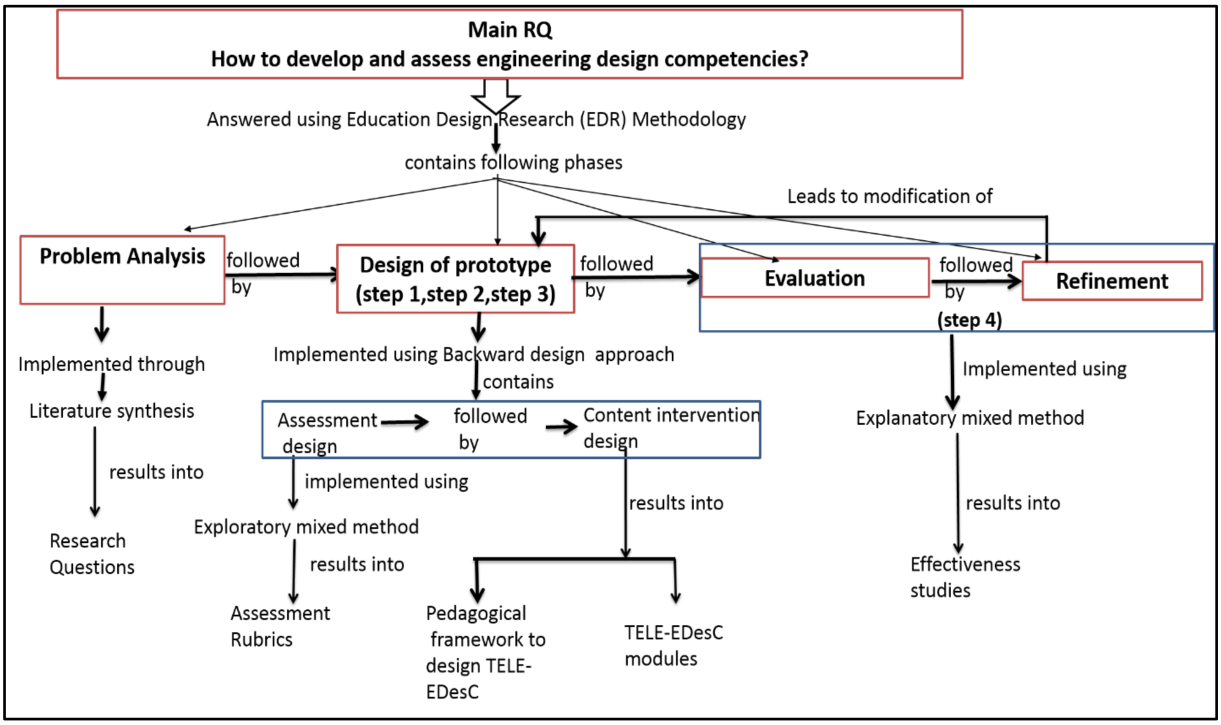


Fig. 1.3. Overview of Research Methodology (EDR)

The next phase is design of prototype, which is carried out using backward design approach (Wiggins, & McTighe, 2005), and answers two research questions that emerged from problem analysis phase. Backward design starts by development of the assessment method followed by design of content intervention. In order to develop instrument we applied exploratory sequential mixed method design.

The development of the assessment instrument for engineering design competencies begins with the process of identifying and defining the specific competencies. Engineering design competencies identified from literature are broadly defined, and lead to multiple possible learning outcomes. Thus it is necessary to operationalize these competencies to small measurable units, which we refer as sub-competencies in this thesis (Step 1, Fig. 1.2). Sub-competencies form the basis of the expected learning outcomes and the assessment criteria. We developed descriptive performance rubrics to assess design competencies based on the sub-competencies of engineering design. We tested the validity, reliability, and usefulness of rubrics (Step 2, Fig. 1.2). The product developed is "Assessment rubrics for engineering design competencies".

Sub-competencies together with rubrics target criteria provided learning outcomes for design competencies. Learning outcomes are applied to develop TELE-EDesC Learning Dialogs. In order to design Learning Dialogs, we followed the approach shown in Fig. 1.2 (Step 3). We first identified metacognitive process to be triggered by using experts thinking action in the design problem solution. Instructional strategies to trigger these metacognitive processes are identified from literature review. Learning Dialogs of TEL environment are designed based on instructional strategies using Instructional Design principles of interactive learning environment. This systematic approach is referred as 'pedagogical frame work to design TELE-EDesC'. This framework is applied to identify Learning Dialogs of TELE-EDesC for SOP competency. This framework provided TELE-EDesC modules of our study.

This 'design of prototype 'phase of EDR (design of prototype) contributed to assessment instrument rubrics, pedagogical framework to design TELE-EDesC and TELE-EDesC learning modules. This phase of EDR covered first three steps mentioned in the solution approach in Fig. 1.2. Research methodology details of this phase are described in Chapters 4 and 5.

The last phase of EDR is evaluation and refinement, which is carried using explanatory mixed design method. In this method quantitative analysis is followed by qualitative analysis. Controlled quasi-experiments with quantitative analysis are conducted to determine the effectiveness of TELE-EDesC learning module. The learning behaviour of students is studied qualitatively. Depending on effectiveness results, the intervention, i.e. TELE-EDesC learning modules are refined. This is carried out iteratively, till students achieve desired competence level. This is fourth step of solution approach (Fig. 1.2). This phase contributed to empirical studies of effectiveness testing for TELE-EDesC. Detailed research method is described in Chapters 6 and 7.

In the final step of solution approach we tested possible extension of our solution beyond scope (Section 1.4). This step is described in detail in Chapter 8.

1.4. Delimitations of the thesis

Engineering design education and developing related design competencies are broad areas. This section describes the delimitations of this thesis in terms of the scope of content of TELE-EDesC learning modules, the scope of engineering design competencies for which the solutions in this thesis are designed, and the scope of the type and level of design problems addressed.

1.4.1. Scope of content

In this thesis, we have developed TELE-EDesC learning materials to teach design competencies within the context of an Electronics Circuits course, which is part of a four-year undergraduate engineering programme in all universities. This course is a foundation course taught at the second year level. Electronics circuits and its design find application in almost all streams of engineering. We have selected topics from the course which have been shown to be important in electronics system design. The major concept selected is amplifier design involving varied but primary concepts, on which design of most electronics circuits depends. Topics include circuits for audio frequency and power amplifier so that students learn to design small signal and large signal amplifiers. The above topics consider both linear region of operation which use active devices such as Bipolar-junction transistors (BJT) and Field Effect transistors (FET) as well as non-linear region of operation which uses OPAMP as the active device. A large range of analog electronics circuits are covered by these topics.

Amplifier design problems also cover a range of specifications depending on variety of applications. This in turn will prepare students to design various practical systems.

1.4.2. Scope of design competencies

Students' ability of engineering design is described in terms of competencies such as Structure Open Problem, Multiple Representation, Information Gathering, Divergent and Convergent Thinking which are all required in the process of design. Each of these competencies is further broken down into sub-competencies. The solution in this thesis consists of three main components – assessment rubrics for engineering design competencies, a pedagogical framework for designing TELE-EDesC modules for engineering design competencies, and TELE-EDesC learning modules for specific engineering design competencies in specific topics.

1) Assessment rubrics are designed for each engineering design competency listed above (Chapter 4). In order to do so, sub-competencies are identified for each competency, which form the basis of the rubrics.
2) Pedagogical framework (Chapter 5) to design TELE-EDesC modules. The detailed framework is developed for Structure Open Problem (SOP) competency. After the framework is applied to design TELE-EDesC learning modules for SOP, which are then evaluated, an attempt is made to extend the framework to other engineering design competencies (Chapter 8).
3) TELE-EDesC learning modules. The majority of learning materials developed in this thesis, that is TELE-EDesC learning modules, are to develop the competency of Structure Open Problem. This competency is chosen as the first step of design is to structure the given design problem, which is often open-ended. Structure Open Problem is reported to be a key competency for engineering design since substantial part of design activity is devoted to structuring and formulation of problem (Cross, 2007), and poor structuring of problem leads to poor design of artefacts (Atman, 1999). All TELE-EDesC modules for SOP competency are empirically tested in this thesis.

1.4.3. Scope of design problem type

Engineering design problems are classified as routine, innovative and creative (Brown & Chandrasekaran, 1989).

In routine design problems, the effective problem decomposition is known. In electronics circuit design problems, effective decomposition of problem means all specifications are known. In routine problems mapping of sub-functions into physical components is clear, that means type of circuits suitable to meet given specifications are mentioned in the problem. The only task is to select appropriate components that optimise well established criteria. This problem is solved using fixed formulae. Designer will decide appropriate formula to be used and calculate component values and select practical values. Decision making scope is limited to selection of practical components for design. For example, "*Design class –B push pull amplifier to deliver power of 2Watt to 8ohm load".*

In this problem type of power amplifier is known so students will recall the circuit. The power rating and load is given so they will calculate appropriate currents, voltages and will select components in the circuit.

Innovative design problems are semi-structured. The top level functional decomposition is known, this means type of circuits like amplifier, filter etc. are mentioned. But physical realisation of sub-functions require considerably more efforts this means designer need to extract all relevant specifications for given application and decide which type of filter or amplifier is suitable in the given application. In this type of problems real world problem is given and multiple solutions are possible. For example "*Design power amplifier to amplify audio signal for paging announcement of supermarket with speaker rating of 8 watt".*

For this type of problems specifications need to be identified by designer and multiple circuits are possible based on identified specifications. Designer need to compare these circuits based on characteristics.

In **creative design problems**, the functional specifications are open ended, effective decomposition is not known and designer need to evaluate multiple options. In these types of problems students can explore variety of solution ideas and analyse pros and cons of proposed ideas *"Design an amplifier for a rock musician who needs to perform in an open-air theatre in front of an audience of a thousand people".*

The learning activities developed in this thesis focus on innovative design problems. The goal in all modules of the learning environment is to guide students to structure open innovative design problems. In addition, in one final study (Chapter 8) we tested the extent to which students who learn with TELE-EDesC modules are able to apply their design competencies to the higher creative level problem.

1.5. Contributions of the thesis

The major thesis contributions are:

- Eight TELE-EDesC modules have been developed for four topics for Structure Open Problem competency, in a range of problems that cover major topics in analog electronics circuit domain.
- Assessment rubrics for engineering design competencies have been developed and validated. The following have been established: content, construct and criterion validity, interrater reliability and usability.
- A pedagogical framework to design TELE-EDesC modules for developing students' engineering design competencies has been proposed and tested. The framework provides the steps to researchers to develop Learning Dialogs of a TEL environment for developing students' engineering design competencies. In particular, the framework prescribes specific Learning Dialogs (and guidelines to create them) for SOP competency – Decision Making Task Questions (DMTQ),Simulative Manipulations, Concept Clarification Questions (CCQ),Self-assessment rubrics, Controlled Animation (CANM),Capsule Recommendations (CR) and Information Box(Info Box)
- Effectiveness study of TELE-EDesC learning modules using quantitative and qualitative analysis is conducted. This study confirmed that Learning Dialogs prescribed by the framework are required to develop Structure Open Problem design competency.

The minor contributions of this thesis are:

- Important competencies and sub-competencies for engineering design thinking have been identified and operationalized into measurable learning outcomes, for domain of analog electronics circuits.
- A template is developed for teachers, content creators of TEL environments, and researchers to design TELE-EDesC modules for SOP in their respective domains. Template contain specific guidelines to prepare content and write Learning Dialogs.

1.6. Organization of the thesis

This thesis is organized as follows. In Chapter 2 related work is reviewed, from which the research questions emerge. Chapter 3 describes the overall research methodology applied. Chapter 4 presents the development and validation of assessment instrument rubrics. Chapter 5 serves a two-fold purpose: it describes the emergence of the pedagogical framework to design TELE-EDesC modules, and demonstrates the application of the framework to design learning modules for SOP competency. Chapters 6 presents the evaluation of TELE-EDesC modules, followed by the application of its results in Chapter 7 to refine TELE-EDesC modules. Chapter 8 describes possible paths of extension of the solution boundaries. Chapter 9 concludes the thesis with a summary and discussion of research questions, exploration of possible future directions. Fig. 1.4 shows organisation and connections of the thesis chapters.

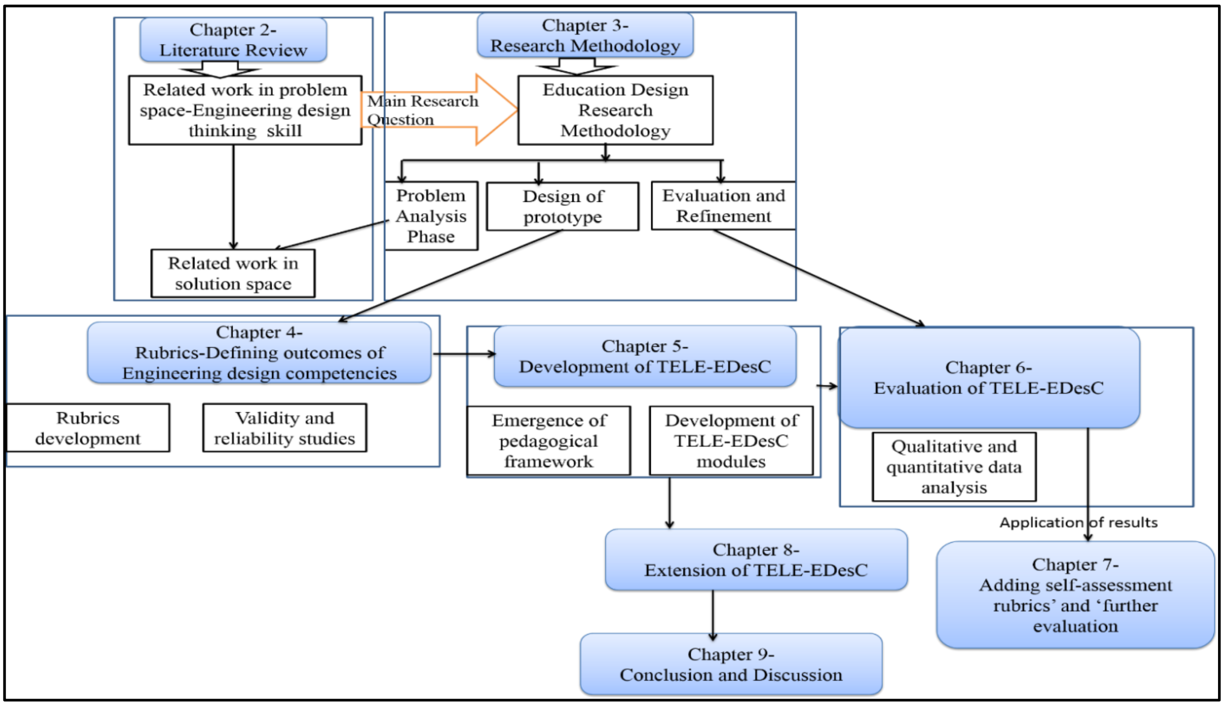


Fig. 1.4. Thesis chapters' organisation and connections

Chapter 2

Literature Review

In Chapter 1, we presented an overview of the research in this thesis that included a brief reference to the literature contributing to the problem of developing engineering design skills. In Chapter 2, we critically analyse and synthesize literature to identify the gaps in existing work and unaddressed research issues. We describe the various areas in which we surveyed existing research, and the reasons behind selecting these areas. This chapter builds the reference framework for design of the TELE-EDesC learning environment to develop engineering design competencies among students. It also provides guidance for the choice of the methodology for the study.

2.1. Organisation of literature review

The literature reviewed in this chapter is organized into themes that form the framework for the 'problem space' and the 'solution space' of this thesis (Fig. 2.1).

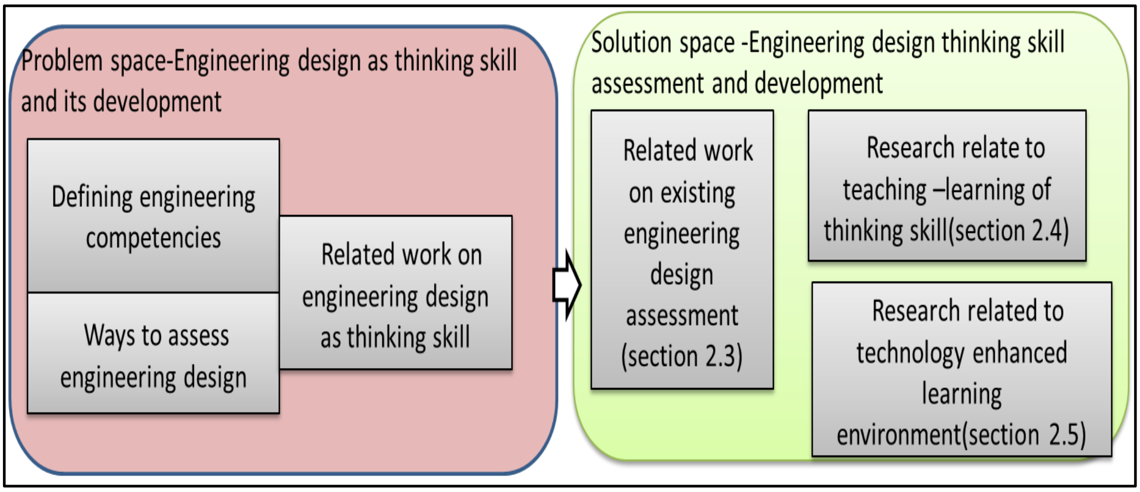


Fig. 2.1. Organisation of related work

We begin the review of literature by surveying different existing ways to teach engineering design. We review the theories underlying engineering design thinking and report the effectiveness of various education methods in terms of the attainment of design competencies by students. In Section 2.2, we describe the parental theory that formed the background of the research problem, that is, what is engineering design. The parental theory contains features of the design thinking process and methods to develop competencies through curriculum or instructional strategies. The analysis of literature on instructional and assessment methods for design education led to the main research problem of the thesis: 'How to develop and assess engineering design competencies?'

We follow a 'backward design' (Wiggins &McTighe, 2005) approach and first focus on the assessment of engineering design competencies. Engineering design is an open-ended task and varied assessment methods are possible. The task complexity further increases when decisions need to be taken for what to assess. Section 2.3 reviews different methods to assess and evaluate students design tasks. The literature review for this section leads to the identification of a suitable approach to assessing engineering competencies, and the need for developing a valid and reliable instrument for doing so.

The next part of the literature review focuses on the solution theories related to the development of engineering design thinking skills. Section 2.4 contains a broad review of solution strategies to develop various thinking skills related to engineering design. In Section 2.5, we explore the features and teaching-learning strategies in technology enhanced learning environments to develop thinking skills and the major components of these technology enabled learning environments.

2.2. Problem space – What is engineering design thinking?

The development of engineering design thinking skill among students is an important goal of engineering education. Professional organizations, accreditation bodies (ABET, 2014) as well as educators (Sheppard, 2003) have emphasized that graduating students should be able to design effective solutions for given needs. However, design thinking is complex and teaching design has been reported to be difficult (Dym, 2005).This section presents the theories underlying engineering design thinking, various methods that are in use to teach engineering design to students, and conceptualizing engineering design in terms of thinking skills (Beyer, 1988).

2.2.1. Defining engineering design thinking

There is lack of a unique definition of what comprises engineering design thinking, and plenty of definitions and perspectives of engineering design thinking abound (Atman, Chimka, Bursic, & Nachtmann, 1999; Crain, Davis, Calkins, & Gentili, 1995). However, what is common in all approaches is that engineering design is a systematic process, in which “designers generate, evaluate, and specify concepts for devices, systems, or processes” (Dym, 2005).The process of engineering design thinking is a systematic and intelligent decision-making process, through which products or artefacts are generated. These artefacts should be as per specifications or customer requirements and need to satisfy constraints. The steps in the design process may start from the problem definition, progress through conceptual design development and end with testing and verifications. The common pattern of activities during design thinking is summarized as generation, evaluation and decision making (Aurisicchio, Ahmed, & Wallace, 2007).

Engineering design thinking is complex cognitive process that results into an open-ended creative task (Dym, 2005). The outcomes of the design process can be predicted and thus the engineering design thinking process is deterministic (Dym, 2005). However, during the design process, many divergent ideas are evoked which also shows the element of randomness in the process. Some researchers have described design as a series of activities and they proposed prescriptive models for these activities (Asimov, 1962; French, 1985; Pahl, Beitz, Feldhusen & Grote, 2007).

In summary, engineering design thinking overall is systematic process, but expects internalisation of complex cognitive inquiry with divergent ideas and systematic decision steps.

2.2.2. Methods to teach engineering design

Engineering design is an ill-defined domain. Its definitions vary from a systematic process (Pahl et.al, 2007; Ullman, 1988; Gero, 1990) of solving open-ended problems, to a creative, innovative and unpredictable process (Dym, 2005). This makes design education itself as an open-ended problem with multiple and diverse opinions about teaching design (Dutson, Todd, Magleby & Sorensen, 1997). Even though design educators have differing opinions, they commonly agree to the fact that design helps in converting knowledge into practical experience (Dutson et al., 1997; Wood, Jensen, Bezdek & Otto, 2001). In universities worldwide, most existing engineering design courses were developed based on principles of providing real world problem solving experience to students (Wood, et al., 2001; Dutson, et al., 1997; Dally & Zhang, 1993). Various approaches are used to teach design ranging from systematic sequential learning activities to open-ended activities. The focus of this section is on the teaching-learning of these courses, from both the teacher's perspective on conduction of design education and students' perspective as value addition for their future development.

Design education mostly started with open-ended problem posing and development of solution to real world problem. One of the first approaches to teaching design was through senior capstone courses (Dutson et al., 1997) and provided an experiential learning activity to students. These courses gave an opportunity to convert analytical knowledge gained in previous courses into hands-on projects in final years. These were full scale projects with extensive use of engineering laboratories, prototypes were designed to solve real world problems. The instructional method was typically project-based learning (Kjersdam & Enemark, 1994) and duration of capstone courses varied from a half semester to two semesters. Faculty members conducted supportive lectures to teach concept of design methods, process, risk evaluations, project management, etc. Limitations in such approaches include the cost in terms of infrastructure, and equipment. The cost can be lowered by assigning small scale projects with limited set of specifications. However, this approach brought its own challenge in terms of increased instructor involvement. Case study methods to teach design are implemented in some universities. In this method, projects are discussed and analysed by faculty members and students. The cost of conduction of this method is very low, but students lack practical design experience (Burton & White, 1999).

Design contests are another method to conduct these capstone courses and products evaluated by peers as well as industry panels provided real time feedback. One of the variants in design courses was experimental designs (Young, Yarranron, Bellehumeur & Svrcek, 2006), and applied to chemical engineering laboratory courses. Students were taught fundamentals related to unit operations in theory classes. They designed and conducted experiments, proposed the processes, collected and interpreted data and justified the results. Effectiveness of the course was described through student's comments. In general these courses were valuable for deeper understanding and provided hands on experience on the field. The subjective evaluation of these courses indicated that teacher and students both appreciated the teaching learning values of these courses. They agreed that such courses helped to connect engineering theory knowledge to hands on practical experience. But in most of the cases cost of conduction was high due to special infrastructure equipment requirements, budget and extra faculty time and effort.

Other approaches include project based learning (PBL), focusing mainly on product development process. PBL approaches have shown positive learning gain (Kolodner et al., 2003) but again the conduction of these courses was time-consuming (Burton & White, 1999; Benjamin & Keenan, 2006). Another approach to teach design was based on reverse engineering (Wood et al., 2001) and known as product evolution or redesign. Reverse engineering is defined as in-depth analysis of existing product to find process of product development and design decisions (Gabriele, 1994). Instructional activity of the course is divided into three phases as reverse engineering, modelling, analysis and redesign. Reverse engineering phase leads to identification of specifications and development of hypothesis, design modelling phase helps to understand design principles of dissected product. Redesign leads to development of the product based on improved specifications. These courses helped students for hands on practical experience and addressed different learning styles of students. The major drawback reported was time commitment from students and they struggled with iteration of design projects (Wood et al., 2001).

Another approach suggested is integration of design across the curriculum (Wilczynski & Douglas, 1995) to develop design thinking process sequentially. Design experience was introduced at entry level considering background and skills of students and revisited throughout the engineering education and ended with true real world design experience of capstone courses. These courses aimed to develop design abilities gradually. Students appreciated the design experience of these courses. The major concern of these types of courses was faculty overload in terms of selection of design problems, addressing student's queries and evaluation of results.

Engineering design in industry is another approach (Dunn-Rankin et al., 1998) which helped teachers and students to learn together the application of engineering fundamentals to industry problems. The course provided opportunity for students to deal with true industry problem and faculty role is not problem poser but partner in problem solution. This process even added value to faculty learning in the way of inquiry method of problem solving. Similar to other capstone courses this course also faced inherent challenges related to cost and faculty overload. But additional challenges included in these courses were bringing companies to campus, protecting confidentiality of projects of the companies and so on.

All the approaches described till now are based on product development through open ended problem solving or sequential teaching learning process of problem solving through learning activities. A different approach to teach design is based on CDIO initiatives and standards (Benjamin & Keenan, 2006). CDIO stands for conceiving, designing, implementing and operating real world systems and products. Multiple Design-Build-Test (DBT) modules were designed for all years with increased level of complexity. Learning outcomes for each DBT module was guided by Bloom's taxonomy. The integrated nature of the modules helped students for immediate application of concepts learnt in theories. These courses helped to acquire professional skills and attributes as well. These courses require extensive involvement of instructors as mentor and metacognitive coaches. Faculty need to keep track of individual team member's skill attainment as well as group project evaluation. Interim feedback from instructor is utmost important for effectiveness of such courses. All these courses were reported to be time consuming and resource intensive (Benjamin & Keenan, 2006; Wood et al., 2001).

Assessment of the student's performance is an integral part of teaching learning process. Since engineering design is an ill-structured open-ended activity, assessment of students' performance in design courses has been reported to be another challenge (Dutson et al., 1997; Wood et al., 2001). There exist a variety of methods and criteria that have been used to assess students' performance in engineering design courses (a detailed review is provided in Section 2.3). However, there is no standard procedure or criteria or instrument to assess achievement of students engineering design thinking skill.

The approaches described in this sub-section focus on courses in engineering curricula to teach and assess design. These courses have been reported to be effective and beneficial to students, especially in promoting student interest and retention (Wood et al., 2001). However, challenges have been reported too in running such face-to-face courses, such as extra faculty time, special training, and lack of assessment techniques. Faculty members need to devote lot of time as course designers, mentors, metacognitive coaches and evaluators. Robust assessment criteria and instruments is another challenge. Thus design courses are not common in universities, which translate into lack of design ability among students (Eckerdal et al., 2006; May & Strong, 2011).

In order to overcome these challenges one of the possibilities can be to develop engineering design as a thinking skill progressively through training sessions instead of conducting semester long design course focusing mainly on product development. In next sub-section we explore engineering design from the perspective of a thinking skill.

2.2.3. Engineering design as a thinking skill

Thinking skills are cognitive processes that human beings apply for sense-making and problem-solving (Beyer, 1988). These cognitive processes are ill-structured tasks and need to be taught to learners. But after training learners can apply these processes and perform these tasks which indicate that these skills may be transferrable. Thinking skills in science and engineering include experimental design, systems thinking, multiple representations, problem-posing, algorithmic thinking, scientific modelling, feasibility analysis, estimation, graphicacy, evidence collection, and data representation and analysis. Thinking skills are pan-domain in nature, that is, they involve a set of common foundational cognitive processes which cross boundaries of domains and have applicability across domains. Researchers have characterized pan-domain thinking skills in a variety of ways, such as trans-disciplinary habits of mind (Mishra, Koehler & Henrikson, 2011), ABET student outcomes (ABET, 2012), science process skills (Padilla, 1990), scientific abilities (Etkina et. al, 2006), 21st Century skills (Pellegrino & Hilton, 2012), computational thinking skills (Wing, 2011; Grover & Pea, 2013) and so on.

ABET student outcomes for engineering education (ABET, 2014) are defined in terms of a graduating student's abilities such as ability to identify and formulate problems, analyse and interpret data, ability to use modern tools etc. One of the expected outcomes of engineering education according to ABET is that "students should be able to solve open ended design problems". Thinking skills important to the learning of fundamental sciences have been labelled as 'science process skills' (www.narst.org) and include students' basic abilities to observe, draw inferences, think of ways to measure, classify into various categories, predict and test the outcomes and so on. Advanced scientific thinking skills expect students to identify variables, formulate hypothesis, gather and interpret data, operationalize variables, and conduct and analyse experiments. Another categorization scheme of thinking skills in the sciences is 'scientific abilities' which are "important procedures, processes, and methods that scientists use when constructing knowledge and when solving experimental problems" (Etkina et al., 2006). These include the ability to represent a scientific process in multiple ways, design experimental investigations, devise, test and modify a qualitative explanation or a quantitative relationship, collect and analyse data, evaluate conceptual claims and problem solutions and communicate. It is expected that students should apply scientific abilities reflectively, critically and deliberately while attempting scientific experiments or problems.

A recent categorization of thinking skills is provided by '21st century skills'. This is based on the demand of a new skillset for 21st century graduates and is guided by ICT integration into education. The skills expected are learning and innovation skills, information media and technology skills, and life and career skills (Pellegrino & Hilton, 2012). Learning and innovation skills prepare students for handling complex life and work environment by developing critical thinking skills and problem solving skills through innovations (Beyer, 1995). Another skill set required in modern era due to technology advancement is computational thinking skills (Wing, 2011; Grover& Pea, 2013). These skills refer to application of computer and modern tools in problem solving process. Hence algorithmic way of approaching solution through logical analysis is the expected skill set. Thinking skills such as problem solving, critical thinking, effective communication, application of technology and planning are expected at the workplace (Pellegrino & Hilton, 2012). Specific cognitive skills for problem solving and critical thinking include decision making, information collection analysis and appropriate interpretation, mathematical and statistical analysis skills, measurement skills and so on (Jonassen, 2000).

In all the above characterizations and categorizations, a frequent thinking skill encountered is that of designing experiments or systems to achieve goals such as investigate phenomena, test hypotheses, and solve problems. Thus engineering design can be considered as a thinking skill, in which the designer not only performs a problem-solving activity but also applies systematic thoughtful, complex cognitive process (Dym, 2005). Engineering design thinking is an iterative decision making process (Sheppard et al., 1997) which is based on fundamental concepts of science, mathematics and engineering (ABET, 1995).

Engineering design thinking requires analysis and synthesis about a system by exploration and guided decisions. The complexity of design thinking process leads to a challenge of operationalization of the skill for progressive development of skill. One of the approaches proposed by ABET engineering accreditation agency is the development of measurable competencies (ABET, 2012), that is, students must demonstrate certain defined criteria which can be assessed. Other researchers too have approached the development of design thinking skill in terms of a competency-based approach. Plonka et al. (Plonka et al., 1994) developed design competencies for manufacturing engineers known as "Greenfield design competencies". These competencies were treated as design specifications and considered as common vision for all parties involved in the process. Competencies are categorized at four levels, that the design engineer will: i) know self and work with others, ii) design, build, and run high value-added, manufacturing systems, iii) solve unstructured problems and iv) lead change. Based on the above work, the competencies have been extended for engineering students (Davis et al., 1997). The engineering design competency categories are: problem definition, information gathering, idea generation, implementation, process improvement and communication. These design competencies are based on expected learning outcomes of design education and are aligned with ABET criteria (WCERTE 1996; ABET, 2000).

Engineering design competencies have also been defined on the basis of cognitive abilities in design thinking (Açar & Rother, 2011; Dym, 2005; Sheppard, 2003; Doyle, 1997; Linder, 1999; Evans, 1990). These abilities consist of series of convergent-divergent thinking, thinking of system dynamics, prediction and reasoning of uncertainties, and use of many design languages. These abilities were detailed into 16 qualities required by design engineers (Sheppard & Jenison, 1997). Furthermore, Adams et al. (Adams, Turns & Atman, 2003) used Schön's reflective practitioner theory (Schön, 1983) to explain importance of structuring open-ended problems. Reflective practitioner emphasizes problem setting activity along with solving it and scopes the problem, find and use multiple information and reason about solution through experimentation. A competency profile for future design engineers is reported in (Robinson, 2005) and includes personal attributes, project management, cognitive strategies, cognitive abilities, technical ability, and communication.

Researchers have also conducted experimental studies with experts and novices to identify engineering design competencies. A series of empirical studies were done by research groups of design education (Atman, Chimka, Bursic & Nachtmann, 1999; Adams, 2001; Cross, 2003) in which design problem solving process of experts and novices is compared using qualitative data analysis. It was found that experts can design high quality product and they gathered more information, defined open ended problem precisely, generated more number of ideas and frequently transit between design steps than novice.

2.2.4. From synthesis of literature to problem definition

In order to develop engineering design thinking among students, one needs to be able to define *what* design thinking means and how it can be measured, for instance, via development of learners' competencies. Thus, one of the first goals in this thesis is to be able to identify an essential common set of engineering design competencies. Towards this goal, we analysed the design competencies described from different perspectives and categorized them.

Table A1.1 in Appendix I contains an analysis of 23 research papers that attempt to characterize engineering design competencies. Table 2.1 below shows a representative sample (a subset of Table A1.1) of various descriptions of design competencies perceived by researchers and educators. This table shows that the nomenclature used by different researchers varies. Some researchers have identified the expected outcomes of design education and referred to them as expected design competencies, others have defined design thinking abilities, while yet others have considered design as a development of various knowledge levels.

Table 2.1: Overview of design competency definitions from various researchers

Design competencies (Davis et al., 1995)	**Design abilities (Sheppard & Jenison, 1997)**	**Design thinking process (Dym, 2005)**	**Design problem activities (Aurisicchio et al., 2007)**	**Expert design process (Atman et al.,1999)**	**Knowledge based design competencies (Ahmed,2007)**
Problem definition	Define and formulate an open-ended and/or under defined problem, including specifications	Consider big view with the help of systems and then thinking of small parts	Designer frames the problem with broader view and connects different issues to create chunks.	Rigorous problem scoping activity correlated to quality of final product	Knowledge about product like explanation, understanding and insights
Idea generation	• Generate alternative solutions • Use analysis to support synthesis • Identify methods or approaches suitable for design • Identify critical technology and approaches, stay abreast of change in professional practice	Series of divergent and convergent questioning.	Generation and establishment of criteria	Thinking of more alternative solutions	Knowledge of specific strategies applied in product development
Evaluation and decision making	• Think with a systems orientation, consider needs of and integrate various facets of the problem • Use a systematic problem solving approach • Recognize the need for and implement iteration	• Make design decisions • Think about system dynamics, predict uncertainty, make estimations	Evaluation and decision steps of design activity	Transition between design steps frequently	

An analysis of the research papers in Table A1.1 showed that the papers were primarily based on one of three approaches described towards the end of Section 2.2.3: papers describing outcome-based competencies (for example, Davis et al 1995), theoretical papers arising out of analysis of cognitive processes involved during design thinking (for example, design abilities in Sheppard, 1997), and empirical studies (for example, those studying expert-novice differences (Atman, 2001). Table 2.1 also shows that while terminologies of design competencies might differ from one researcher to another, there is a common set of learning outcomes expected from students in the design thinking process.

In order to identify this set of engineering design competencies, we mapped the common as well as frequently appearing definitions with each other. Then we categorised these competencies under a common heading which will lead to same or similar type of design thinking amongst students. For example, the concept of idea generation (Crain et al.,1995; Davis et.al., 1995) expects that students should think about solution in multiple ways, whereas the same idea is described as generating alternative solutions (Sheppard, 2003) and experts have been shown to think of more number of alternative solutions (Atman, 2001). This is categorised as 'divergent thinking competency' of engineering design thinking in this thesis.

Table 2.2 shows examples of mapping of similar competencies that have been referred to using different terminology. The fourth column in Table 2.2 shows the categories identified (italicized). The categories that emerged from this synthesis are: Structure Open Problem, Multiple Representations, Information Gathering, Divergent Thinking and Convergent Thinking. The last column in Table 2.2 contains a working definition of these identified categories of engineering design competencies.

Table 2.2 forms the basis of the problem definition of this thesis. The main focus of research in this thesis is the development of engineering design thinking skill via development of competencies. This approach is intricately tied to the assessment of engineering design thinking since the achievement of the design competencies can be measured once a suitable technique and instrument are determined (Section 2.3 and Chapter 4 contain details). The focus of the assessment shifts from the evaluation of the design product to the progressive tracking of design competencies, potentially reflecting the development of the thinking skill. Thus the main research question (RQ) of this thesis is:

How to develop and assess engineering design competencies?

Table 2.2. Mapping of competencies from different research papers

Theory based (cognitive process)	**Experimental results based**	**Competency based**	**Outcome of synthesis (Identified competencies)**	**Definitions**
System thinking and estimating problem	Rigorous problem scoping activity is correlated to quality of final product	Problem definition	*Structure open problem*	Identification and formulation of problem for given specifications.
Use of many languages of design	Concept sketching correlated to successful designs	Utilize graphical and visual representations and thinking	*Multiple Representations*	Sketching various valid representations while designing product and also maintaining consistency between different representations.
Find information and use variety of resources.	Experts gather more information	Information Gathering	*Information Gathering*	Identifying relevant sources of information and using them accurately to gather relevant information
Series of divergent questioning and making decisions	More alternative solutions developed by experts compared to novice	Idea generation	*Divergent thinking*	Thinking for different relevant possible solutions based on specifications, principles, pros and cons analysis. Suggesting different solutions as well as different methods of solving the problem while considering constraints.
Thinking about the system design by thinking about system dynamics, predicting uncertainty, making estimations	Transition between various solution steps, evaluating solutions based on criteria and decision making	Evaluation and decision making	*Convergent thinking*	Selecting accurate solutions based on principles and constraints, justifying selected solutions, making suitable and valid assumptions. Using formulae accurately and working out overall solution in proper steps.

Fig. 2.2 summarizes the areas of literature reviewed in Sections 2.2.1 - 2.2.4 to define the problem and arrive at the main RQ of the thesis.

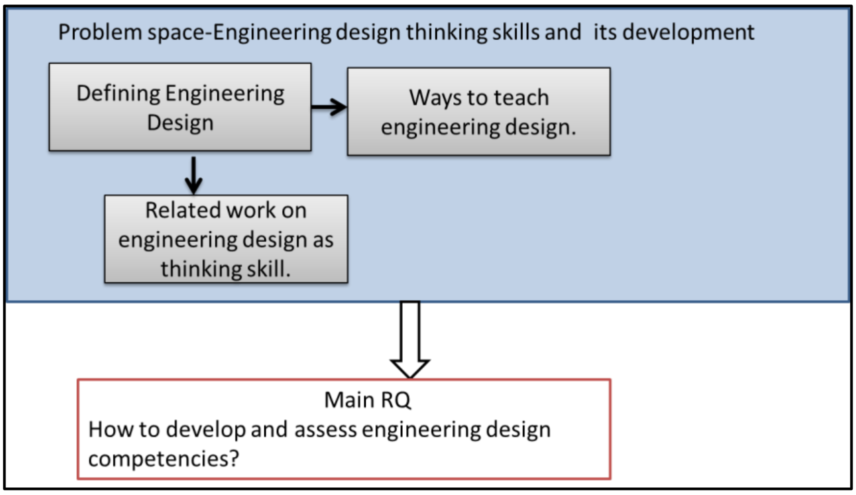


Fig. 2.2. Summary of literature review of problem space

2.2.5. Literature review towards a solution approach – an overview

The above research question considered in the thesis suggests further literature that must be reviewed in order to find a solution approach. As briefly mentioned in the Section 2.1, we use a backward design approach for the solution: a teaching-learning environment for engineering design competencies. Backward design has been recommended as an alternative to traditional curriculum design since it identifies a clear understanding of the 'destination' of the educational process as well as how to get there. In the backward design approach, the desired results are first identified (in this case, outcomes based on engineering design competencies), then assessment measures, strategies and instruments that will provide evidence for the above results are defined, and finally instructional activities are designed to achieve the desired results (Wiggins & McTighe, 2005). Keeping in line with the above solution approach, we reviewed literature in the following areas:

- Assessment strategies and instruments for engineering design competencies (Section 2.3). The goal is to identify a suitable assessment strategy for a complex and ill-structured task such as engineering design, and ultimately develop robust assessment instruments that can not only evaluate students' performance but also guide them in the achievement of engineering design competencies.
- Strategies for teaching-learning of thinking skills that can be used to develop students' engineering design competencies (Section 2.4). By reviewing the theories that lead to

the successful teaching-learning strategies of thinking skills related to engineering design, my goal is to identify common pedagogical principles, cognitive processes and instructional strategies and learning activities that can be used to develop the teaching-learning environment for engineering design competencies.

2.3. Assessment of engineering design

2.3.1. Assessing design products and processes

Assessment of engineering design competencies is a complex tasks with lot many options varying from product evaluation to process evaluation using different criteria. The ill-defined structure of engineering design education is applicable to assessment area as well, with multiple processes used to assess student's achievement of design abilities. There have been several efforts at assessing students' performance in design courses. The effectiveness of implementation of design courses is typically monitored using students' performances in the courses. Since most of the courses expected design product development, the most common method of assessment was product evaluation (Sobek & Jain, 2004; Scott & Merwe, 2003). Some methods rely on assessing students' design documents (Fentiman & Demel, 1995) while others evaluate final products assessed by experts. In some methods, students' presentation of their final design is assessed by predetermined criteria, (Brockman, 1996; Mankin, 2007) whereas in others, evaluation is done through design contests (Gregson & Little, 1999). Multiple approaches like presentation evaluation, product evaluation, and course evaluation have been applied for assessment in some courses (Scott & Merwe, 2003; Petkov & Petkova, 2006). The purpose of the above assessment methods is to evaluate outcomes of teaching courses using different criteria and varied deliverables to assess the design product.

Researchers have gone beyond the analysis of the products of design, and also analysed the thinking process involved during design. Verbal protocols have been analysed to compare design thinking process of experts and novice students (Atman et al., 1999; Adams, 2001; Cross, 2004). For example, in a first year engineering course, students' intellectual development due to a design course is assessed via semi-structured interviews (Marra et al., 2000). These interviews are rated and students' intellectual development is assessed based on Perry's model.

The purpose of assessment goes beyond merely evaluating students' performance. An important function of assessment is to provide students timely feedback on their work, so that they can take steps to improve their learning (Gibbs & Simpson, 2003). Assessment can be a powerful tool in promoting students' learning, but only if the assessment method defines the parameters precisely and conveys specific, easily understandable criteria to students (Black & Wiliam, 1998). This emphasizes the need for a robust and reliable assessment instrument. Assessment instruments should provide clear, precise and detailed feedback to students on the level of their performance (Arter & McTighe, 2001). In addition, instruments that promote self- and peer-assessment have been shown to be effective in promoting student learning (Black & Wiliam, 1998).

There have been efforts to develop and use such assessment instruments for engineering design. In a course on Information Systems, multiple assessment strategies are used to evaluate students' performance on a design project. Instruments used to assess these projects include standard tests, checklists, questionnaires, marks sheets and scoring rubrics (Scott & Merwe, 2003). An instance of an assessment instrument that specifies categories of performance is Team Design Skill Growth Survey (TIDEE) (Trevisan et al., 1999). TIDEE contains various competency categories such as teamwork, information gathering, problem definition, idea generation, evaluation and decision making, implementation and communication. A questionnaire based on TIDEE was used for evaluating final presentations and students' answers to short questions in a design course. In addition, a self-assessment survey based on TIDEE is used by students to self-assess their class emphasis and personal growth (Mankin, 2007).

2.3.2. Rubrics as an assessment instrument

An important category of instruments which have been recommended for their ability to promote "assessment for learning" (Dochy, Gijbels & Segers, 2006) are *rubrics*. "Rubrics are descriptive rating scales which consist of pre- established performance criteria to evaluate student's performance or product resulting from performance task" (Mertler, 2001). Rubrics have been suggested as a suitable instrument to evaluate open ended activities (Bailey & Szabo, 2007) like design. Rubrics are known for their capacity to enhance deep learning amongst students by providing rich, detailed and specific feedback to students about their performance (Arter & McTighe, 2001; Wiggins, 1998). They encourage self-learning. Their ability to assess higher order thinking skills of students (Etkina et al., 2006) make them useful assessment instrument. The goal of rubrics is for students understand the target concept or ability they are expected to achieve and the criteria to achieve that ability. To address this goal, rubrics provide formative feedback not only at the target level of performance, but also at all intermediate levels, thereby helping students assess their own efforts relative to the target criteria.

Rubrics have been employed to some extent to assess learning of engineering design. Platanitis et al (Platanitis & Pop-Iliev, 2010; Platanitis, Pop-Iliev & Nokleby, 2009) have developed 'ICE' rubrics to assess students' learning process via design products in a mechanical engineering course. These rubrics assess each component of a design project, such as, background search, brainstorming and selection of a concept on the criteria of idea, connection and extension (ICE). For course of information systems Scott et.al developed rubrics to evaluate student's group project (Scott & Merwe, 2003). Final presentation of design products was evaluated based on documentation, user interface, security, robustness and integrity, innovation, scope and functionality, and extras. Bailey & Szabo (Bailey & Szabo, 2007) have developed rubrics to assess students' design process knowledge. Rubrics are used to assess design of shopping cart and criteria cover different aspects of engineering design and specific instructional objectives. The scoring criteria include needs, idea generation, analysis and decisions, building and testing, layout and iterations, time and documentation. Trevisan et al (Trevisan, Davis, Calkin, Gentil, 1999) developed rubrics to assess students' competencies of design. These rubrics assess design course outcomes based on three categories, namely design process, communication and teamwork (Trevisan et al.; Davis et al., 2002).

2.3.3. Need for new assessment instrument

While rubrics exist for assessing design in a variety of contexts, most existing rubrics are broad and a single criterion covers many learning outcomes. Thus it is difficult to apply rubrics and identify which competencies are developed and which need improvement. Criteria used in existing rubrics have been developed either for general design (such as that of a shopping cart) or for a topics other than electronics (such as mechanical engineering). Thus they cannot be directly used by an instructor or a researcher to assess competencies needed for electronics circuit design, which is the scope of this thesis. In some rubrics such as ICE (Platanitis & Pop-Iliev, 2010) the evaluation criteria are mainly based on students' level of knowledge application and covers stepwise progress in student's thinking process, but the scoring description is provided only for target performance level. Other performance levels are not mentioned. Finally, the validity and reliability of existing rubrics have not been reported, thus highlighting the need for an instrument whose robustness has been explicitly established. This establishes the need to develop rubrics to assess engineering design competencies within the context of this thesis. The research question addressed is:

RQ.1. How to assess engineering design competencies?

This section reviewed assessment techniques, which belongs to the step of 'deciding acceptable levels of evidence for expected outcomes' in the backward design approach mentioned in Section 2.1. The next step of the backward design approach is to identify instructional strategies and activities to develop the desired outcomes in students. In this thesis, since the development of engineering design is considered as a thinking skill, the following two sections review the teaching-learning of thinking skills with the goal to identify theoretical foundations and instructional strategies that have been reported to teach these skills. In Section 2.4, recommended strategies to teach thinking skills are discussed. Engineering design thinking is examined from the perspective of the thinking skills of ill-structured problem solving, inquiry and decision-making. Section 2.5 discusses the TEL environments with it benefits and applications to develop thinking skills.

2.4. Teaching-learning of thinking skills

Thinking skills are sense making cognitive processes applied for problem solving. It is expected that students should apply these skills in new situations. In Section 2.2.3, we have argued that engineering design can be considered as a thinking skill and combines the thinking processes needed for ill-structured problem solving (Cross, 2004), inquiry learning (Dym, 2005) and decision-making (Aurisicchio et al., 2007). In Sections 2.4.1-2.4.3 we review literature on recommended teaching-learning strategies for each of these. Section 2.4.4 summarizes the key features of teaching-learning strategies for thinking skills and discusses implications.

2.4.1. Ill-structured problem solving

Engineering design involves problem solving activities and any problem solving activity can be defined as a “goal driven sequence of cognitive operations” (Anderson, 2005). In an engineering design problem, the goals or specification of design are undefined, there are multiple possible and feasible solutions which forces designer to take decisions at various steps. Design problems expect the designer to estimate the solution, make assumptions and justify the solution.

Complex ill-structured problem solving requires both cognitive and metacognitive skills. Cognitive skills include domain specific knowledge (Chi & Glaser, 1985; Voss & Post 1988; Voss et al., 1991 referred in Ge & Land, 2003) as well as structural knowledge (Chi & Glaser, 1985 referred in Ge & Land, 2003). In engineering design, domain specific knowledge includes application of essential and relevant concepts or principles in selected domain. Structural knowledge includes making meaningful connections between domain knowledge (Jonassen, 1997). Structural knowledge in engineering design is appropriate use of these principles while designing products. Metacognitive skills are defined as “planning, monitoring and evaluation of self–learning (Flavell, 1979; Wineburg, 1998 referred in Ge & Land, 2004). Metacognitive skills include both knowledge of cognition and regulation of cognition. Knowledge of cognition is processes which guide a learner about selection of appropriate strategies and their application (Schraw & Dennison, 1994). Regulation of cognition includes monitoring, evaluation and planning through self-cognitive efforts and reflection (Xun & Land, 2004).

Scaffolding or external support has been extensively used to develop metacognitive requirements of open-ended problem-solving process. An empirical study (Xun & Land, 2004) showed that scaffolding through question prompts improved students open-ended problem solving ability. The same authors described a conceptual framework to design these question prompts. Some guidelines to write question prompts are as follows:

1) Question prompts should reflect content domain experts thinking.

2) Questions should address common misconceptions of students and allow students to reflect on their thinking.

3) Question prompts should be able to connect prior knowledge of students. Questions should be sequenced so that it will help students to complete the task.

In order to acquire complex thinking required to develop ill-structured problem solving skill the learning environment should include complete learning task in problem context. Scaffolds in the task should provide supportive information to connect learner with prior knowledge. Procedural guides and part test practice should be provided for developing problem solving skills (van Merriënboer et al., 2002; Kim & Hannafin, 2011). Complex tasks can be designed using problematizing aspects of subject matter (Reiser, 2002). Problematizing aspect refers to focussing students' attention to situations which need to be resolved, engaging students to reason the aspects of problems and take decisions. Problematizing aspect will make tasks interesting and force students to pay attention to resolving the issues. Tasks should allow students to construct arguments and explanations (Aleven & Koedinger, 2002) through visualisations and representations (Linn, Clark et al., 2003). Problem solving aspect can also be strengthen by structuring the task ((Reiser, 2004) in the learning environment.

2.4.2. Inquiry learning

Engineering design thinking reflects complex inquiry process and investigative learning environments can help to develop inquiry learning. Inquiry learning is an activity in which students individually or collectively investigate phenomenon, interpret it and draw conclusions. Students are supported in all the activities of learning by prompting to frame questions, planning the activity and justifying their inferences (de Jong & van Joolingen, 1998).

An important strategy recommended to develop science process skills such as hypothesis generation and evidence evaluation is self-directed experimentation. In this strategy self-initiated activities were developed, which help learners to understand relation between multiple variable as well as their cause-effect relationship. Use of self-explanatory prompts or reflection prompts in self-directed experimentation (Kuhn & Phelps 1982; Chi, 1996; Haussmann & Chi, 2002) environment helped retention of skills among learners. An important feature is hands-on manipulation which gives learners control of variables and promotes inquiry based investigation (Zimmerman, 2007).

Inquiry learning curricula such as ISLE (Etkina et al., 2007), based on cognitive apprenticeship (Brown, Collins, & Duguid, 1989; Collins et al., 1989) have been shown to promote learning in face-to-face classes. This learning environment contains scaffolded inquiry cycles supported by formative assessment and was shown to develop interpretive knowledge required to learn scientific abilities (Etkina et al., 2010).

2.4.3. Decision-making

Engineering design process involves a series of decisions to be made even for the simplest products to be designed (Aurisicchio et al., 2007). Decision is defined as “judgement weighing the arguments supporting or opposing the options for a particular issue” (Ullman & D’Amboise, 1995). Decision-making is thus ability to select appropriate options and eliminate irrelevant options based on systematic reasoning skills (Bögeholz, 2006). Decision-making process requires through integration of evidence to support decisions as well as pros and cons analysis of all possible options. The major goal of decision making process is to eliminate options through judgements and keep appropriate ones.

In order to develop decision-making competence in design deep reasoning questions have been proposed, followed by decision-based options and information prompts. Such questions promote convergent thinking. In addition, generative design questions were suggested for showing multiple possible options in design decisions (Aurisicchio et al., 2007).

2.4.4. Summary and implications of teaching-learning of thinking skills

The goal of Section 2.4 was to identify possible strategies to teach engineering design as a thinking skill. Two major approaches to teach thinking skills required for engineering design, such as complex problem solving, inquiry learning and decision-making, are problem-based learning (Hmelo-Silver et al., 2004) and inquiry learning (Kuhn et al., 2000). These approaches provide the necessary complex learning environment and engage learners in the knowledge construction process (Linn, Clark & Slotta, 2003). In both approaches students are prepared for content as well as discipline based reasoning skills, self-directed learning skills and collaborative investigation or problem solving (Hmelo-Silver, 2006). Both these approaches engage students in sense making cognitive processes (Zimmerman, 2007). In both learning environments students are exposed to explorations through problems during which they collect and analyse data through various resources to solve problems.

Scaffolding is an integral part of most learning environments that focus on the learning of thinking skills. The guidelines for effective scaffolding methods to achieve optimal results have been discussed by various researchers (Guzdial et. al, 1996; Hmelo-Silver, 2006; Quintana et al., 2004; Reiser et al., 2002). Scaffolds in the form of reasoning prompts guide for applying appropriate reason strategies (Derry et al., 2006; White & Frederiksen, 1998). Scaffolding provided through questions (Kim & Hannafin, 2011) focuses students' attention to elements of scientific process. Learning environments should provide learners with opportunities of exploration, experimentation and reflection (Jonassen, 2000). Experimentation guided by scaffolds like focussing questions, self-assessment rubrics and reflection prompts has been recommended as an instructional strategy for developing scientific abilities (Etkina et al., 2010).

Fig. 2.3 summarizes strategies suggested for teaching thinking skills in general and specific strategies helpful to teach thinking processes involved in engineering design thinking process.

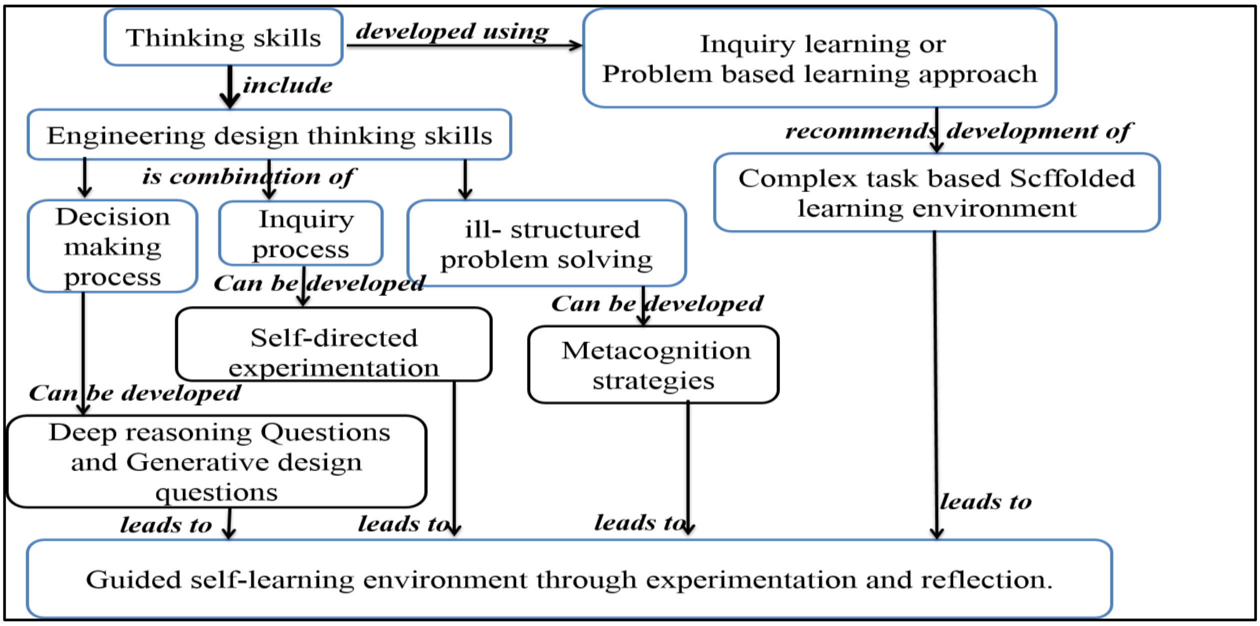


Fig. 2.3. Learning environment and instructional strategies for developing thinking skills

Researchers have recommended that learning of thinking skills need complex learning environments that provide students the opportunities to experiment, engage them in sense-making processes and offer strategies for formative assessment (Black & Wiliam, 1998). One approach to developing such learning environments is by harnessing the affordance of modern technology (Reiser, 2004). Current day ICT based tools can provide the necessary support for creating a teaching-learning environment to develop and assess engineering design competencies. Thus, another important area of literature that we review in this chapter is:

- Technology enhanced learning (TEL) environments and learning components therein for the development of thinking skills (Section 2.5). As mentioned in Section 2.2.2, a key challenge in the teaching of engineering design is that it is resource intensive. A possible solution is to develop a technology-based self-learning environment to students that can support existing curricula.

2.5. Technology Enhanced Learning (TEL) Environments

Technology enhanced learning (TEL) environments are broadly considered as any form of instruction where technologies are used to facilitate and enhance learning process (Goodyear & Retails, 2010). Technology based learning environments have been referred in various forms as tools and systems for understanding concepts, developing thinking skills and for effective communication and collaboration (Bruce & Levin, 1997; Jonassen, 2000; Conole & Dyke, 2004). TEL environments with simulations allow systematic exploration of hypothetical situations, allow learners to change time scale of events, allow interaction with simplified versions of process (Veermans et al., 2006). Such active engagement of learners with environment promotes authentic inquiry practices. Interactive simulations in TEL environments are effective learning tools for scientific thinking (Lindgren & Schwartz, 2009). Simulations can provide multiple representations. For science and engineering education, interactive visualizations promote scientific discovery learning and constructivist knowledge acquisition. TEL environments with interactive simulations provide possibility to manipulate, access required information, store information which help to develop experimentation skill.

The affordances of ICT have led in recent years to the development of TEL environments to promote various thinking skills such as modelling ability, scientific argumentation and problem-solving. In the next section 2.5.1, some TEL environments are reviewed with a focus on their main features and learning components. In Section 2.5.2, the design principles of TEL environments are discussed.

One of the important design components of TEL environments is the availability of self-regulation. Self-regulation helps learner to plan, monitor and evaluate self-learning which develops metacognitive strategies among students needed for complex problem solving. Technology can change nature of complex task by allowing learner to focus on productive part by providing automated guidance based on learner's interactions. This is automating aspect of task for learners by limiting part of task learner need to perform (Reiser, 2004).

2.5.1. TEL environments for thinking skills

There exist several TEL environments whose goal is to promote students' scientific reasoning and inquiry skills. This section reviews five such widely used TEL environments at the K-12 level such as WISE, Co-Lab, WiMVT, Go-Lab and Apple Tree.

WISE, i.e. Web-based Inquiry Science Environment (Linn, Clark & Slotta, 2002) is an adaptive learning environment whose main goal is to harness the science thinking among students through knowledge integration. Knowledge integration is the process of evoking student ideas, supplying innovative ideas to their list and then supporting the process of categorisation, organisation and reflection for improvement of conceptual understanding. WISE incorporates prompts which allow students to reflect and monitor their progress. The key ideas applied in WISE are making science accessible, making thinking visible, helping students to learn from each other and promoting lifelong learning. To make science accessible, various activities like inquiry questions, inquiry maps, pivotal cases etc. are added in WISE. Thinking visibility was developed for students by allowing students to test their ideas against criteria. To make teachers thinking visible to students, facility to provide feedback and grading of students report is available in WISE. In order to make scientific phenomenon visible to students, models, simulations are present. Peer learning facility is introduced through inquiry map and online asynchronous discussion.

Co-Lab (van Joolingen, de Jong, Lazonder, Savelsbergh & Manlove, 2004) is a discovery based learning environment designed for learning inquiry and modelling. Learners collaboratively conduct and analyse experiments through simulations or remote laboratories. A built-in modelling tool supports hypothesis construction and experiment design, and systems dynamic models of the scientific phenomenon. Graphical tools are available to learners to plot experimental results and compare results for various experiments of simulation. A process-coordinator tool in Co-Lab scaffolds learners via ‘process displays’ and ‘process prompts’ and provide support for data interpretation and model revision. The facilities of the support tools are slowly reduced as the learner’s acquisition of self-regulatory skills increase. This control is then passed from one learner to another. Chat tool supports students’ interaction and locator tool allow tracing the non-participative members of group.

Web-based inquirer with Modelling and Visualization Technology (WiMVT) (Sun & Looi, 2012) is a model based science learning environment based on principles of guided inquiry, modelling and visualization, and social interaction. This system is designed for developing conceptual understanding as well as critical thinking skills such as reasoning skills and reflective thinking skills. This system has four main components such as functional component, instructional content, assessment and scaffolds. This system is based on principle of Predict-Observe-Explain of modelling, also contains Pre-model phase. Students draw models based on their knowledge resources before investigations and they may modify models or draw new models. This feature is helpful to teachers to monitor progression in students modelling ability as well as students to think and reflect about their modelling ability. This system applies eight phases of inquiry cycle such as Contextualize, Question & Hypothesize (Q&H), Pre-model, Plan, Investigate, Model, Reflect, and Apply.

Go-Labs provide online and virtual labs with data set or analysis tool and together referred as “online labs”. Pedagogically structured learning space is provided for teacher to systematically embed these labs in the instructions. Students are provided instructional guidance and collaboration opportunities with online labs. Pedagogical approach of Go-Lab is based on guided inquiry, in which guidance is provided in two forms. First form is set of phases based on inquiry cycle and second form is guidance at each phase. Go-Lab provides scaffolds like hypothesis scratchpad, experiment design tool .These all elements provide inquiry learning space of Go-Lab. Teachers are provided with facility to develop dedicated learning space. Go-Lab project is developed with objectives to improve conceptual understanding in science domain.

Apple Tree (Chen et al., 2013) is a TEL environment developed for assessing collaborative argumentation skill in school learning. Three main scaffolding mechanisms embed in Apple Tree are dual representational and interactional spaces, automated assessment for learning, and staged-based collaboration scripts. Representational space allows user to represent arguments using graphs and chat tool provide discussion space. Assessment is visible to students at two levels one at individual level and second at group level. Assessment is three dimensional based on unit of assessment, time of assessment and aspect of assessment. A stage based collaboration scripts added for guiding argumentation sequence. The Apple Tree features are based on constructing arguments, assessing arguments with instant feedback and guidance to construct arguments principles.

Table 2.3 shows a comparison of common learning components of TEL environments described above.

Table 2.3. Common TEL environment learning features

TEL Environment / Design feature	WISE	CO-LAB	WiMVT	Go-Lab	Apple Tree
Skill/Knowledge targeted	Scientific thinking	Experimentation skill	Modelling skill	Conceptual understanding	Assessment of Argumentation skill
Education theory/principles	Knowledge integration	Discovery learning	Guided Inquiry	Guided inquiry	Collaborative learning and formative assessment
Visualisations	Simulations ,graphing tools	Simulations	Simulations	Virtual labs and simulations	No
Interactivity	Variable Manipulation	variable manipulation	Variable manipulation	Variable manipulation	Responding
Modelling tools	Yes	Yes	Yes	No	No
Reflection facility	Yes	Yes	Yes	Yes	Yes
Collaborative learning facility	Yes	Yes	Yes	Yes	Yes(high priority)
Graphical tool	No	Yes	No	Yes	No

Table 2.4 shows that the some of the prominent features of TEL environments to teach inquiry are simulations with high interactivity like variable manipulation, graphical tools, modelling tools with collaborative learning facility. These TEL environment support guided inquiry process with scaffolding mechanism. In order to design these interactive scaffolds interactivity design principles need to be followed. In the next section we review design principles which guide the design of such TEL environments. These principles suggest the type of learning activities, sequence of activities, methods to develop activities etc.to maximise learning gains without cognitively loading learners.

2.5.2. Design principles of TEL environments

An important feature of TEL environments is interactivity, which represents the characteristic of learning environments enabling multidirectional communication between the learner and the environment. This interactivity should be designed to assist learners in meaningful knowledge construction thus meeting learning goals (Markus, 1990; Puntambekar et al., 2003; Rouet, 2006; Rouet & Potelle, 2005). Discovery-based learning is critical feature in many inquiry learning environments. Interactive visualizations provide relevant information at key discovery points and thus focus learners' attention on the discovery. Interactive visualizations also help knowledge building by annotating connections between old and new information.

Interactivity has also been recommended to facilitate deep cognitive processing in learners (Moreno & Mayer, 2007). Five common types of interactivity listed are dialoguing, controlling, manipulating, searching, and navigating. Interactivity by dialoguing means learner can ask question and receive answer or can answer question and receive feedback. In controlling learner can control pace of learning episodes. In manipulations learner can explore simulations by setting up different variables. In searching information acquisition is supported by entering query, receiving options and selecting options. In navigating learner controls episodes of learning by selecting from various available sources. These interactivity types need to be selected carefully to avoid cognitive load on learner. Five guiding principles are suggested to reduce cognitive load and improve motivation of students towards learning. These principles are guided activity, reflection, feedback, pacing, and pre-training (Moreno & Mayer, 2007). Guided activity principle helps learners to select, organize and integrate new information. This principle emphasizes need of guided exploration in discovery learning (de Jong, 2005). Reflection promotes meaningful learning by encouraging students for systematic information organization. Explanatory feedback reduces extraneous processing which reduce cognitive load. Pace control provides learner to process small chunks of information and reduces burden of representational holdings. This principle indicates need of learner control in the learning environment to avoid processing of extraneous information. Pre-training relates learner's prior knowledge to new information.

Interactive visualizations include simulations and animations which can activate prior content knowledge and help to restructure the knowledge (Friedler, Nachmias, & Linn, 1990; de Jong, 2006a). Learning with simulations triggers inquiry cycle. Interactive visualizations that allow learner to change variables and compare various cases can lead to idea generation (Kuhn & Dean, 2005; Keselman, 2003; and foster conceptual reasoning (Zhang et al., 2004).

Dynamically linked multiple representations are often used in animations and simulations. This is another design feature that has been shown to develop deep and abstract knowledge (van der Meij & de Jong, 2006). To decide what type of representation to provide, Tversky et al. (Tversky, Morrison, & Betrancourt, 2002) showed that use of schematic is more beneficial than using realistic picture. Guidance in discovery environments can be provided using domain related information or advice on actions timings, help to sort information etc. (Mayer, 2004).

Feedback is another effective feature of simulation and promotes learning and transfer of skills (Moreno & Mayer, 2007) Explanatory feedback is more effective compared to corrective feedback (Moreno & Mayer, 2007).

2.5.3. Research questions arising from literature review

In Section 2.2.4, we proposed the main broad research question of this thesis –'How to develop and assess engineering design competencies' – that arose out of a review of the literature of the problem space. Section 2.3.3 gave rise to the first research question to be investigated – RQ.1 – 'How to assess engineering design competencies'.

Sections 2.5.1 and 2.5.2 give rise to a further research question related to the development of TEL environment for engineering design competencies. Majority of TEL environments for inquiry learning have been developed for science education at the K-12 level, and there are fewer TEL environments at the tertiary engineering education level. The learning goals of most existing TEL environments are teaching domain-related concepts or scientific reasoning skills (such as modelling, hypothesis testing etc.). There have not been TEL environment reported to teach engineering design competencies. Hence, one research question identified for this thesis is:

RQ 2. How to develop TEL environment to teach engineering design competencies?

Fig. 2.4 summarizes the areas of literature reviewed in Sections 2.3 - 2.5 to identify research issues in the solution space.

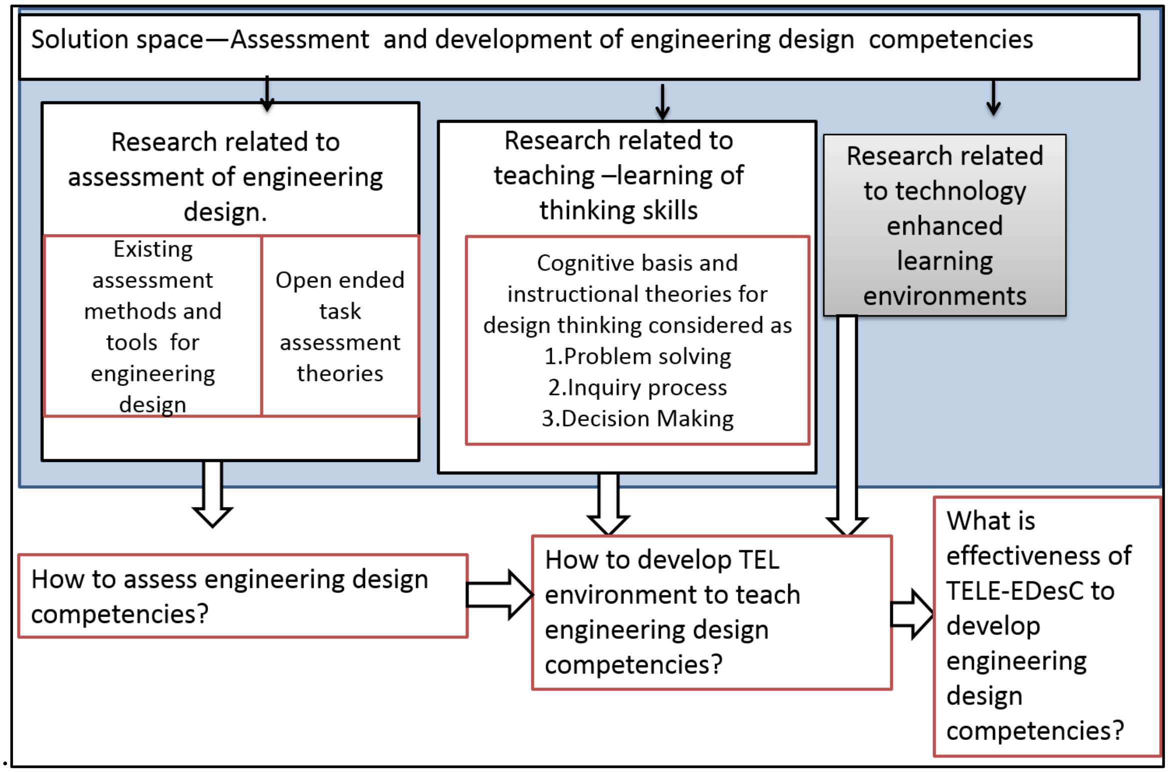


Fig. 2.4. Organisation of related work in solution space

This chapter reviewed the literature which serves as a theoretical basis for deciding assessments strategies and instructional strategies to develop a TEL environment to teach engineering design competencies. The research method implemented to address the research questions related to assessment and development of TEL environment is presented in Chapter 3. Chapter 4 describes the actual implementation process for assessment instrument development. Chapter 5 presents the process of development of the TEL environment for engineering design competencies. The TEL environment to develop engineering design competencies is referred as 'TELE-EDesC'. TELE-EDesC is tested for learning effectiveness and the following research question is investigated:

RQ3. What is the effectiveness of TELE-EDesC to develop engineering design competencies?

Fig. 2.5 summarizes the outcome of literature review of this thesis which led to the research questions.

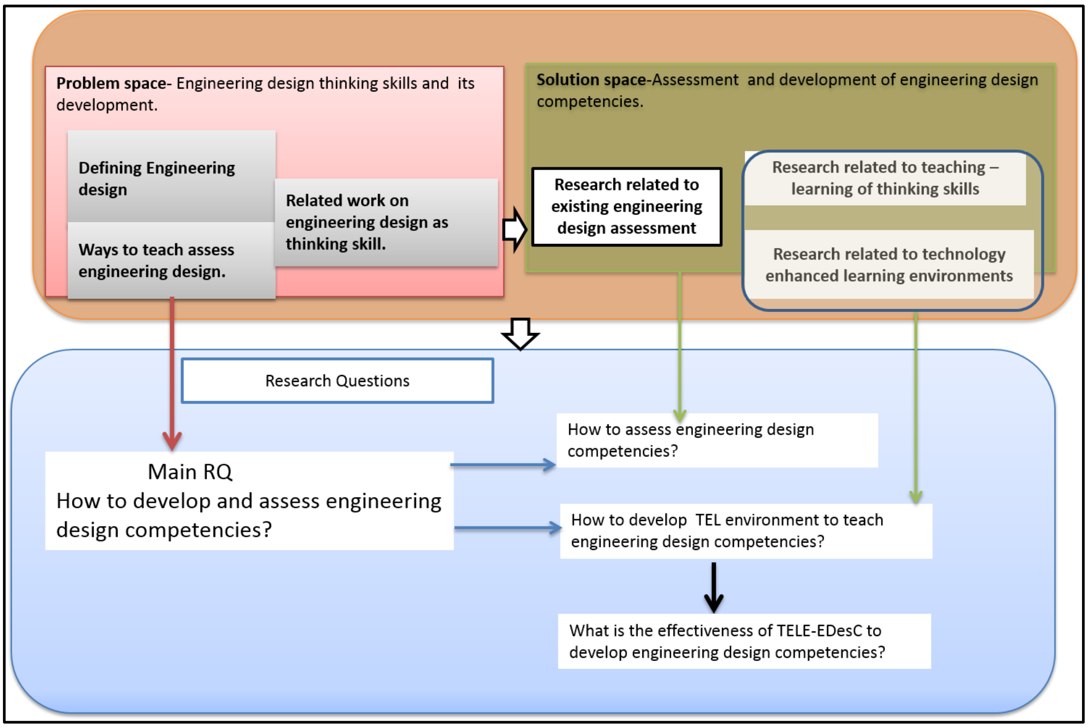


Fig. 2.5. Outcomes of literature review leading to research questions

Chapter 3

Research Method

The literature review in Chapter 2 indicated the complexity of engineering design thinking, as well as the challenges of development and assessment of design thinking skill. Detailed analysis of related work further provided insight into the possibility of characterising design thinking in terms of measurable design competencies, which include Structure Open Problem, Multiple Representations, Information Gathering, Divergent Thinking, Convergent thinking. This chapter presents an overview of the research method applied to answer the main research question of the thesis, 'How to develop and assess engineering design competencies?'

As explained in Introduction, Section 1.3, the overall research method is based on Education Research Method (Van den Akker, 2012). The first phase of EDR is problem analysis, which was carried in this thesis by analysing and synthesizing literature (Chapter 2). The literature survey gave rise to specific research questions for assessment of design competencies and the development of Technology Enhanced Learning (TEL) environment to teach engineering design thinking skill. The second phase of EDR focuses on prototype design. Backward design approach (Wiggins &McTighe, 2005) was used to implement this phase. This phase of EDR provided the framework to develop the TEL environment and learning modules (called TELE-EDesC modules) for engineering design competencies. Implementation of this phase is described in Chapters 4 and 5. The third phase is evaluation phase in which TELE-EDesC modules were evaluated for Structure Open Problem competency for learning effectiveness. The fourth and last phase of EDR is the refinement phase, and is conducted using explanatory method. Section 3.1 to 3.3 describes phases of research EDR with specific research questions and outcomes.

Fig. 3.1 describes main phases of EDR with implementation process and outcomes of each phase.

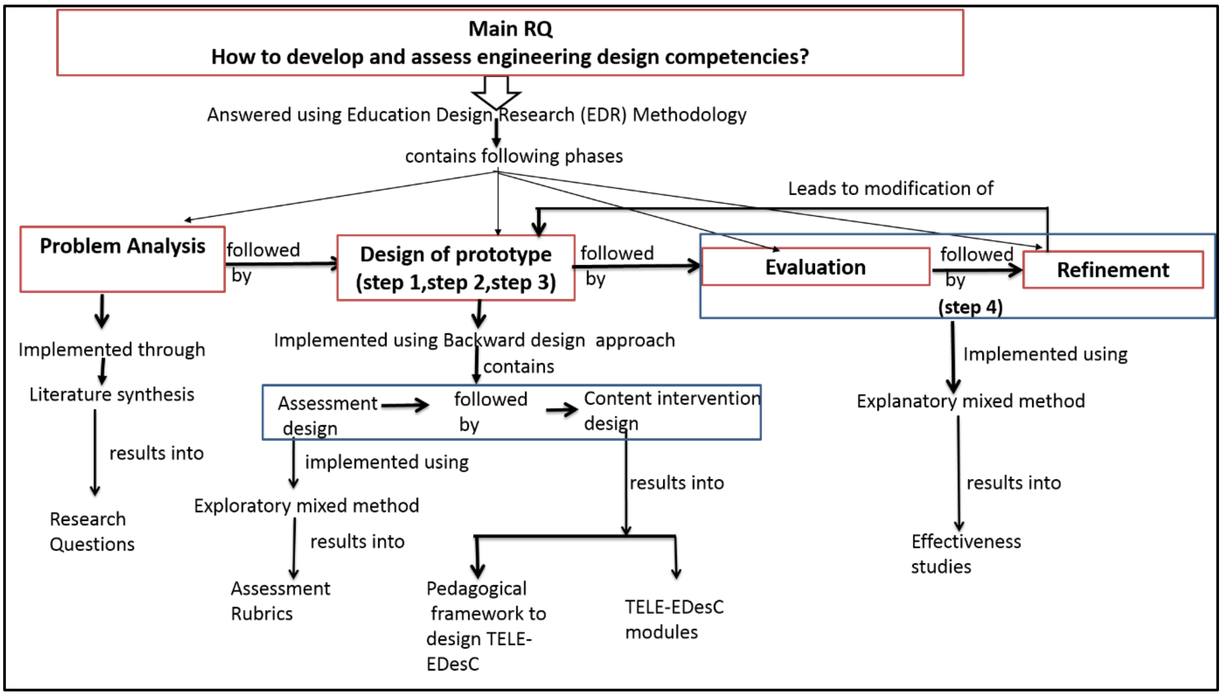


Fig. 3.1. Overview of Education Design Research Method (reproduced from chapter 1 fig 1.3)

3.1. Problem analysis phase

The problem analysis phase of EDR consists of analysis and synthesis of reported research on various aspects of engineering design as a thinking skill. This analysis was described in detail in Chapter 2: Literature Review. This section provides a summary of the key points arising out of the review.

The problem analysis phase provided specific research questions of the study, shown in Fig. 2.5. Engineering design is a complex cognitive process and has been defined in various ways. Analysis of research in this area provided direction to this thesis to characterise engineering design thinking skill in terms of measurable competencies. This analysis helped identify a common consensus among researchers and educators of what is meant by engineering design thinking. It was found that even though terminologies for engineering design competencies differ, they carry a similar meaning. A common set of competencies that comprise engineering design was identified: Structure Open Problem, Information Gathering, Multiple Representations, Divergent Thinking and Convergent Thinking. Further steps in problem analysis phase indicated that many assessment techniques for measurement of engineering design competencies focus on product evaluation and fewer for design thinking development. This led to the research question "How to assess engineering design competencies?

Engineering design thinking involves a combination of varied complex thinking processes such as ill structured problem solving, decision making, and inquiry learning. Research from science education, cognitive science and educational psychology was reviewed to identify strategies for the teaching of such complex thinking processes (Sec 2.4). What emerged was the need for guided exploratory learning environments containing learning activities promoting the above complex thinking processes. Further recommendations include the use of current information and communication technology to build such environments. Analysis of existing TEL environments indicated a lack of such environments that target engineering design thinking skill. This led to the next research question of the thesis: "How to develop TEL environment to teach engineering design competencies?"

3.2. Design prototype phase

This is the product development phase of EDR methodology and is implemented using backward design method, which is, "keeping the end in mind while developing interventions for teaching" (Wiggins & McTighe, 2005). In this thesis, the focus is the development of engineering competencies, which are the targeted learning outcomes of the intervention. Since the final outcomes are known, backward design is a suitable method to develop the teaching-learning intervention. Backward design contains three major steps as defining learning outcomes, creating assessment techniques and instruments, and developing instructional intervention. The products developed at the end of this phase are assessment rubrics for engineering design competencies & learning modules to teach engineering design competencies (TELE-EDesC modules).

The first two steps of backward design method were implemented using exploratory, sequential mixed method research design. Mixed method research approach consists of "collecting, analysing and integrating qualitative and quantitative research in a single study" (Creswell & Clark, 2007). The advantage of mixed method is that a combination of qualitative and quantitative methods together provides better inferences and triangulation, findings from one method can be explained using results from another method, and one phase of study can lead into another. Exploratory sequential mixed method is applied when a theoretical framework is not available or an instrument is not available. In an exploratory sequential mixed method, qualitative analysis is carried out first followed by quantitative method.

In this thesis, the first step towards development of the assessment technique and instrument was a qualitative content analysis of experts' solutions of engineering design problems. This led to the identification of specific criteria for assessment of engineering design competencies. These criteria formed the basis of the assessment instrument. Once a draft of the instrument was developed, quantitative studies were used to test the instrument for validity, reliability and usability. This phase led to the development of a validated assessment instrument for engineering design competency and answered the research question "How to assess engineering design competencies?" The development and testing of the assessment instrument is explained in detail in Chapter 4.

The third step in the backward design approach is developing teaching-learning strategies and interventions. In this thesis, this step led to the development of a TEL environment for engineering design competencies (referred as TELE-EDesC). TELE-EDesC is developed using iterative design and development approach. We developed learning outcomes based on sub-competencies and target performance (identified in first two steps). Our objective of designing TELE-EDesC is to help learner to attain these learning outcomes. We conducted qualitative analysis of experts design thinking actions (N=05) to attain desired learning outcomes. The common actions under various outcomes grouped together to form categories of actions. Instructional strategies to trigger these actions are identified using learning science principles. Further these strategies are developed into learning actions of TELE-EDesC using Instructional Design principles of Interactive learning environment.

This final step of backward design contributed to eight TELE-EDesC modules (in four topics) and a pedagogical framework to develop TELE-EDesC. The framework provides steps to identify learning activities of TELE-EDesC for engineering design competencies. This framework is operationalised for structure open problem competency for the topic from analog electronics domain.

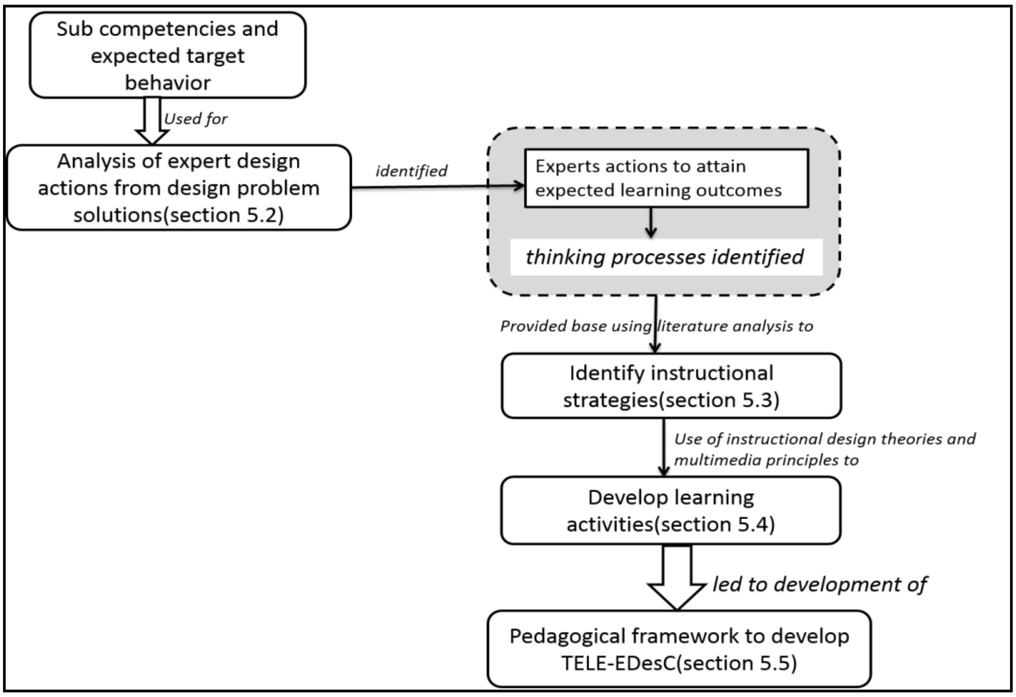


Fig. 3.2. Steps of design prototype phase of EDR

In order to help teachers and researcher to design TELE-EDesC modules for SOP, guidelines are developed and templatized. Template consists of guidelines to select the content, guidelines to write learning objectives and to write Learning Dialogs. It also includes sequencing of steps for writing various activities in TELE-EDesC. This phase answered research question of "How to develop TEL environment to teach engineering design competencies?" This step is described in Chapter 5 in detail. The steps of research method for design prototype phase of EDR are summarized in Fig. 3.3.

3.3. Evaluation and refinement phase

This is last phase of EDR in which the product is tested and refined iteratively (Fig. 3.4). In this thesis, this phase is executed using explanatory mixed method research design. In this method, a quantitative study is carried out first followed by a qualitative study, which is conducted to explain the results obtained from the quantitative study. Thus the research design is named as 'explanatory method'. This method is used when the research questions are more quantitatively oriented and all important variables and measuring instruments are known. The results of the quantitative method trigger new research questions that pertain to understanding the mechanism underlying the results, which then leads to another round of (qualitative) data collection. The research methodology to conduct quantitative study is explained in brief which describes sample in the study, instrument used, procedure and data analysis methods.

Sample:

Participants were second year engineering students from Electronics and allied branches such as Electronics and communication. They studied electronics circuits' related course in their previous semester. All these students are from various colleges of Mumbai University and located in urban, semi-urban and rural areas. These colleges conduct entry level tests for admission and the sample covered the low entry level to high entry level college.

Procedure:

Two sets of instructional materials were developed for each topic, one for the experimental group and the other for the control group. The materials for each group were digital in nature. The materials for each group were intended for student self-learning, that is, without any instruction from a teacher. The experimental group received the materials in the form of TELE-EDesC modules. Control group received materials in the form of interactive slides.

Instrument:

Students design scripts are assessed using rubrics. The rubrics contain a 4-point ordinal scale: Missing, Inadequate, Needs Improvement and Target Performance.

Data Analysis:

Rubrics scores are ordinal data the scores of experimental group and control group are compared using Mann-Whitney test. This test applied when ordering of scores is required. In rubrics score 0,1,2,3 are not uniformly spaced so ordering of scores and comparing them is required. The data analysed in this thesis is non parametric so the nonparametric tests like Mann-Whiteny and K-W are conducted.

The evaluation and refinement phase answered the research question "What is the effectiveness of the TELE-EDesC to develop engineering design competencies?" Once the TELE-EDesC learning environment was developed in the design prototype phase, controlled experiments were conducted in this phase to test its effectiveness. Quantitative data analysis was carried out to measure students' development of engineering design competencies through TELE-EDesC, students' learning pattern was studied using qualitative analysis of screen capture data as students learnt via TELE-EDesC.

The results of qualitative analysis were applied to refine the activities and features in the TELE-EDesC learning modules, and tested again. This iterative process of refinement and evaluation was continued till the desired learning outcomes, i.e. attainment of design competency were obtained.

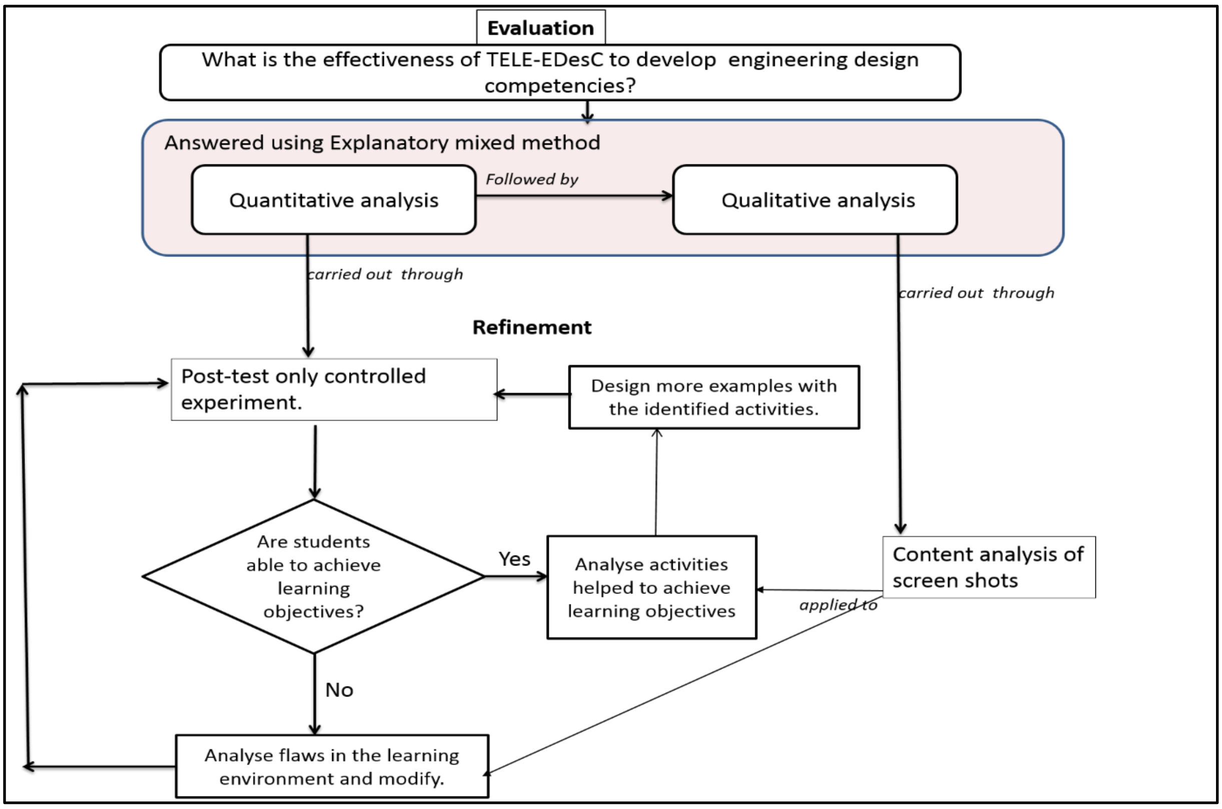


Fig. 3.3. Evaluation and refinement phase of EDR

3.4. Ethical considerations

As with any research involving human participants, ethical considerations needed to be followed (Cohen, Manion & Morrison, 2000). The following guidelines have been followed in this thesis for studies involving human participants:

- Informed consent.

Students were given consent form before start of the experiments and filled these forms before participating in the experiment. Thus written consent of students is available. They were given flexibility to leave the experiment at any point of time. Identity details and background was mentioned in the consent form.

- Anonymity and confidentiality.

Students were assured that this data has no connection with their term work or test marks. They were also informed in writing that this data is only for research purpose and confidentiality will be maintained. In the form their identity is not revealed.

3.5. Summary

This chapter explained how the main research questions (Fig. 2.5) were answered using a broad Education Design Research method (EDR). EDR has four phases: problem analysis, prototype design, evaluation and refinement. Problem analysis phase is carried out using analysis and synthesis of related work. Specific research questions are the outcomes of problem analysis phase. Prototype is designed using backward design approach in which assessment designed first followed by learning environment. The assessment instrument, framework to design TELE-EDesC and TELE-EDesC learning modules are the products of prototype design phase. These prototype products are evaluated and refined using explanatory mixed design method. Empirical studies of effectiveness testing confirmed learning activities required to develop SOP design competencies.

Chapter 4

Rubrics: Operationalization and assessment of engineering design competencies

In previous chapters, we described the need to develop a technology enhanced learning environment for engineering design competencies (Chapter 2) and the overall research method to be used (Chapter 3). We use an outcome based backward design approach to design the technology enhanced learning environment for our goals. The previous two chapters led to the specific research questions for the thesis (summarized in Fig. 2.5).

This chapter focuses on the research question RQ1: 'How to assess engineering design competencies?' The overall goal of this chapter is to describe the process of creating and validating an assessment instrument for engineering design competencies. This is part of the 'design prototype' phase of education design research, the overarching methodology of this thesis (Chapter 3). The product designed at the end of this chapter is engineering design assessment rubrics that have been tested for validity, reliability and usability. We address this goal by implementing the first two steps of backward design: defining the expected outcomes of the learning process and determining acceptable levels of evidence by planning the assessments.

In Section 4.1 we describe the specific research design applied to answer RQ1 – exploratory sequential mixed method. In Section 4.2, we implement the research method and operationalize engineering design competencies into measurable units. For the assessment of complex, open-ended activities such as design, our literature review showed that rubrics are a suitable and powerful instrument (Section 2.3.2). Sections 4.3-4.5 in this chapter describe the process of creation, validation and usability testing of rubrics as an assessment instrument for engineering design competencies. Towards the conclusion of this chapter (Section 4.6), we discuss how to interpret scores of the assessment rubrics in terms of learners' achievement of engineering design.

4.1. Research Design: Exploratory sequential mixed method

The research design applied to answer RQ1 is an exploratory sequential mixed method design. This research design follows a four-step process (Creswell et.al, 2003):

- Step 1: Qualitative method, which is used to operationalize engineering design competencies into measurable units, which we label as 'sub-competencies'.
- Step 2: Intermediate step involving interface design, to connect the qualitative and quantitative methods. This is used to develop assessment instrument.
- Step 3: Quantitative method, which is used to validate the assessment instrument.
- Step 4: Connecting results from Steps 1-3 and interpretation resulted into development of learning outcome.

Fig. 4.1 shows the steps of exploratory design applied in this research.

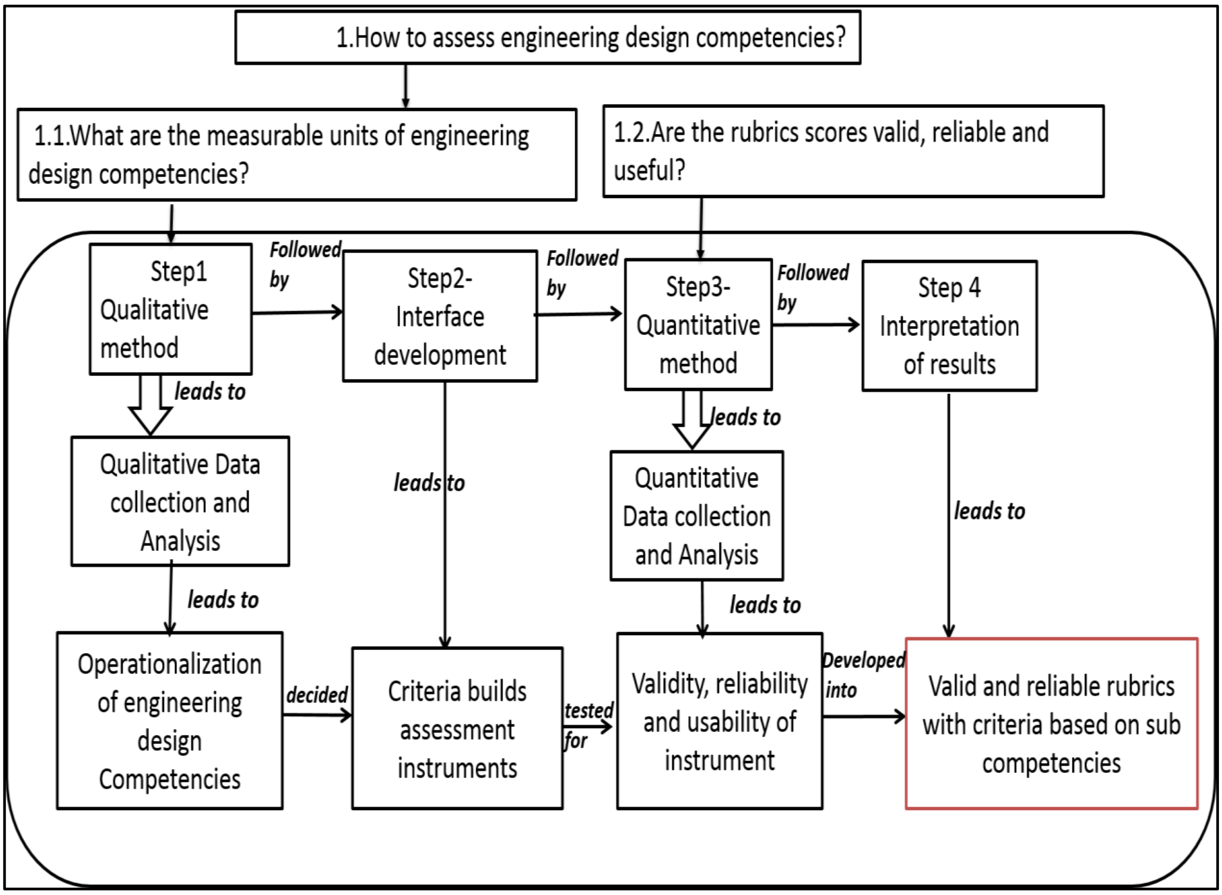


Fig. 4.1. Steps of exploratory sequential mixed research design

4.1.1. Step 1: Qualitative method to identify engineering design competencies

Exploratory research design starts with a qualitative exploration of the topic. This method is applied when a theoretical framework is not available or an instrument is not available. The process of exploration is required in our case to identify measurable units for engineering design competencies, as there are different ways to define these competencies leading to multiple learning outcomes. Secondly the scope of research work in this thesis was restricted to electronic circuits and allied domains. Hence there was a need to operationalize engineering design competencies within these domains. Thus the first step of exploratory method was to carry out qualitative analysis to identify the measurable units of competencies. The above qualitative method is more dominant in this design.

The research question addressed in this step is a sub-question of RQ.1.1: 'What are the measurable units of engineering design competencies?' (Fig. 4.1) The data source is scripts of experts' design solutions. The experts are engineering college faculty members who had more than 10 years teaching experience in the domain of analog electronics. 5 such faculty members are chosen from engineering colleges affiliated to Mumbai University. Each faculty member had taught a design course multiple times. These faculty members were given an open design problem and asked to write its detailed solution. The design solutions were analysed using content analysis method, with the individual steps of the solution considered as the unit of analysis. The codes were assigned based on the design competencies identified from the literature survey. All design steps for each competency were clubbed together and further analysed for identifying measurable units under each competency category. These measurable units are referred as sub-competencies. Sub-competencies are measurable units of main competency and form criteria for assessment of main competencies. Results of this step are explained in Section 4.2.

4.1.2. Step 2: Building on qualitative results to design assessment instrument

In this intermediate step, an interface needs to be designed to connect the qualitative and quantitative methods. The interface in this study is the assessment instrument (Fig. 4.1). The sub-competencies identified in Step 1 are used as the first step towards designing the assessment instrument. The instrument developed to assess engineering design competencies is in the form of rubrics, which are descriptive rating scales consisting of pre-established performance criteria to evaluate students' performance or product resulting from performance task (Mertler, 2001). The engineering design sub-competencies identified from the qualitative analysis were used as evaluation criteria of the rubrics. Additionally, the scoring scheme and performance levels of the rubrics were decided based on the content analysis of experts' design solutions.

Once a preliminary version of the rubrics was drafted, they were applied to students' solutions of design problems. 5 students from third year Electronics and Telecommunication engineering wrote solutions to an open design problem. These solutions were assessed by two researchers (the author of this thesis and the thesis advisor). Scores were first allotted independently by the two researchers without discussion. After assessing individual solutions, the scores and their justification were discussed. Rubrics items for which the two researchers had differing scores were modified and the process was repeated till consistency was achieved. Section 4.3 describes the process and results of the initial draft of the rubrics.

4.1.3. Step 3: Quantitative method to establish validity, reliability and usability of assessment instrument

The research question addressed in this method is RQ1.2: 'Are the rubrics scores valid, reliable and useful?' (Fig. 4.1) For any assessment instrument, it is important that the scores and its interpretations should be valid and reliable. Validity of an instrument needs to be established from multiple perspectives, for example, instrument should assess what it intended to assess, and it should cover the intended domain completely. In this thesis, the intended purpose of the rubrics was to assess engineering design competencies within the defined domains, thus the rubrics items should cover all types of problems in the domain of electronic circuits. Quantitative analysis was carried out by testing rubrics with multiple solutions of students and experts to different design problems.

The rubrics were tested for the following different types of validity and reliability:

- *Content validity* was established by discussing rubrics items and its scoring description with 4 experts one after another. (The experts were 4 faculty members with 5 years' experience teaching analog electronics design). Changes suggested by the first expert were incorporated in the rubrics, and then validated with the next expert, and so on.
- *Construct validity* is interpreted as a response process (Docktor, 2009) that is; "to what extent the assessment instrument assesses design thinking process actually engaged in by individuals." To demonstrate construct validity, 20 design solutions of second year students of Electronics and Telecommunication to an open design problem on amplifier circuit were scored using the rubrics. Design solutions of experts for the same design question were scored. For rubrics to demonstrate construct validity, it was expected that experts would score higher than students, and that there would be a range of scores in students' solutions reflecting their differing abilities.
- *Criterion validity* was established by checking consistency of rubrics scores of student design solutions with an independent evaluation criterion. The closeness of the two evaluation methods was investigated by correlation coefficient.
- In addition, the rubrics scores allotted by different raters to same problem should be consistent. This was established using *inter-rater reliability*.

Finally, the usability of the rubrics was tested by using the System Usability Scale (SUS) (Bangor et.al, 2009) which is a reliable tool to determine the usability of the various products by its primary users, i.e. electronics design course instructors. The SUS survey consists of a 10-item questionnaire with five response options ranging from Strongly Agree to Strongly Disagree. A sample item is: "I thought the rubrics are easy to use". Instructors of an electronics circuit design course were asked to use the rubrics for the first time to assess students' written solutions to a design problem and they filled the SUS. Section 4.4 contains the results of the validity, reliability and usability of the rubrics.

4.1.4. Step 4: Interconnection of results

The last step in the exploratory design is interpreting qualitative and quantitative results and connecting them to establish generalizability of qualitative result (Fig. 4.1). The result of qualitative study is measurable small units of engineering design competencies referred as sub-competencies. Sub-competencies provided basis to define assessment criteria of rubrics which further helped to define specific measurable learning outcomes of each design competency. These learning outcomes guided us to define learning objectives of instructional intervention (described in Chapter 5). A valid, reliable useful engineering design rubric is the product emerged from quantitative study. Rubrics provided assessment solution to track progressive development of engineering design competencies. Quantitative study showed that engineering design rubrics can assess range of design problems from analog circuit domain, rubrics captures the design competence applied by experts as well as students and consistent with other grading criteria applied by teachers. Engineering design rubrics also useful to teachers to assess complex design problems.

4.2. Identifying measurable units of engineering design competencies

The set of design competencies which form the basis of the rubrics are structure open problem (SOP), multiple representations (MR), information gathering (IG),divergent thinking (DIV) and convergent thinking (CONV) (Section 2.2.3). Each of these competencies was identified from a synthesis of literature (Section 2.2.4). Table 4.1 shows the definition of these competencies. It was found that each competency could lead to many valid outcomes. For example, ‘convergent thinking’ involves several outcomes such as: selecting accurate solutions, justifying selected solutions, making suitable and valid assumptions. Each of these needs to be independently measured since the ultimate objective is to assess students’ achievement of the competency in terms of measurable units. This leads to the need for further break down major competencies into small measurable units which are referred as sub-competencies.

Table 4.1. Design competencies and definition (repeated from relevant columns of Table 2.2).

Design Competency	Definition
Structure open problem(SOP)	Identification and formulation of problem for given specifications.
Multiple Representation (MR)	Sketching various valid representations while designing product and also maintaining consistency between different representations.
Information Gathering (IG)	Identifying relevant sources of information and using them accurately to gather relevant information
Divergent Thinking (DIV)	Thinking for different relevant possible solutions based on specifications, principles, pros and cons analysis. Suggesting different solutions as well as different methods of solving the problem while considering constraints.
Convergent Thinking (CONV)	Selecting accurate solutions based on principles and constraints, justifying selected solutions, making suitable and valid assumptions. Using formulae accurately and working out overall solution in proper steps.

4.2.1. Breaking up of a design competency into sub-competencies

To obtain specific measurable sub-competencies for each engineering design competency, we carried out content analysis of experts' solutions to a design problem. Experts were engineering faculty members (N=5) with more than 10 years design teaching experience. Individual steps of the solution were used as the unit of analysis. The codes were decided using competencies identified from literature and the relevant design steps were classified under these codes. For example, as per Structure Open Problem (SOP) definition, the steps related to specifications will be coded under SOP code. When the design steps were categorised, it was found that four categories were emerged for SOP: Identification of specifications, use of specifications, sequencing of design steps and writing structured design statement. Fig. 4.2 shows an example of a design solution of an expert and coding of design steps.

Design problem: Design a power supply to convert 110VAC line voltage to DC with following specifications Vout: no less than 20, Ripple about 2V,load current=1A(max)

Sample 1. Ac mains voltage =110VAC is converted to dc, so power supply block circuit will be drawn which contains transformer, rectifier, filter and regulator. -------- *Decide structures based on specifications*

Fuse should be applied to primary side which will protect the circuit from sudden mishaps like transformer failures. Rectifier selected to design the power supply are full wave bridge rectifier because half wave rectifier even though components are less give rise to high ripple factor and conversion efficiency is only 40%.

-------------*Decide structure based on specifications*

20V output voltage is expected from power supply which is after ripple of 2V. Thus we need to pick up Vout(peak) two volts more than expected value around 22V.

Bridge rectifier is preferred as rectifier and it contains 4 diode, so drop across diode should be considered and appro.1 V drop is assumed (2 diodes) Transformer should thus provide voltage =23V.(peak).-----------------*Identify specifications*

Transformer ratings are always given as rms value so V_{rms} should be calculated. ----------------- *identify specifications*

We will design transformer circuit first and thus need to calculate rating of transformer-----------------Decide design step sequence.

CODE: Structure Open Problem

Fig. 4.2. Part of content analysis from sample solution of expert

Table 4.2 shows the set of specific sub-competencies for the ‘all design competencies. Once we have identified measurable units, that is, sub-competencies for each individual competency, we proceeded to decide the performance levels of each sub-competency. Performance levels were decided by developing assessment rubrics for competencies and sub-competencies.

Table 4.2. Design competencies and its sub-competencies

Design Competency	**Sub-competencies**
Structure open problem	1) Identify specifications from given open ended problem. 2) Decide structure based on specifications. 3) Implement design steps sequentially. 4) Write problem statement in structured manner.
Information Gathering (IG)	1) Decide all relevant sources of information 2) Use sources to extract relevant information.
Multiple Representation (MR)	1) Construct valid representation for given design problem 2) Justify consistency between different representations required in design problems 3) Apply representations to solve design problem.
Divergent Thinking (DIV)	1) Write multiple solution ideas for given problem 2) Suggest multiple solutions based on specifications / constraints. 3) Analyse multiple solutions based on pros and cons 4) Analyse solutions using different problem solving methods.
Convergent Thinking (CONV)	1) Select appropriate solution based on pros-cons analysis 2) Select solution based on principles. 3) Justify chosen solution. 4) Evaluate solution based on constraints. 5) Write assumptions for solving the problem. 6) Justify assumptions. 7) write complete solution using appropriate mathematical formulae

4.3. Constructing rubrics to assess engineering design competencies

According to Mertler (2001) “Rubrics are descriptive rating scales which consist of pre- established performance criteria to evaluate student’s performance or product resulting from performance task”. The ‘pre-established performance criteria’ in these assessment rubrics are based on the specific sub-competencies (Table 4.2). The steps in the process are drafting of initial version of rubrics, testing and iteration. The initial version was drafted based on sub-competencies as rubrics items, and target and lower levels of performance were written. To test the initial draft of the rubrics, students’ solutions of design problems were assessed. 5 students from third year electronics engineering each wrote solutions to an open-ended design problem. These solutions were assessed by two researchers (thesis author and advisor) and scores were allotted independently. After assessing all solutions, both scorers discussed the agreement between their scores. The rubrics items with different scores for the same solution were discussed and their wording modified if necessary, to reduce ambiguity. Fig. 4.3 shows the steps.

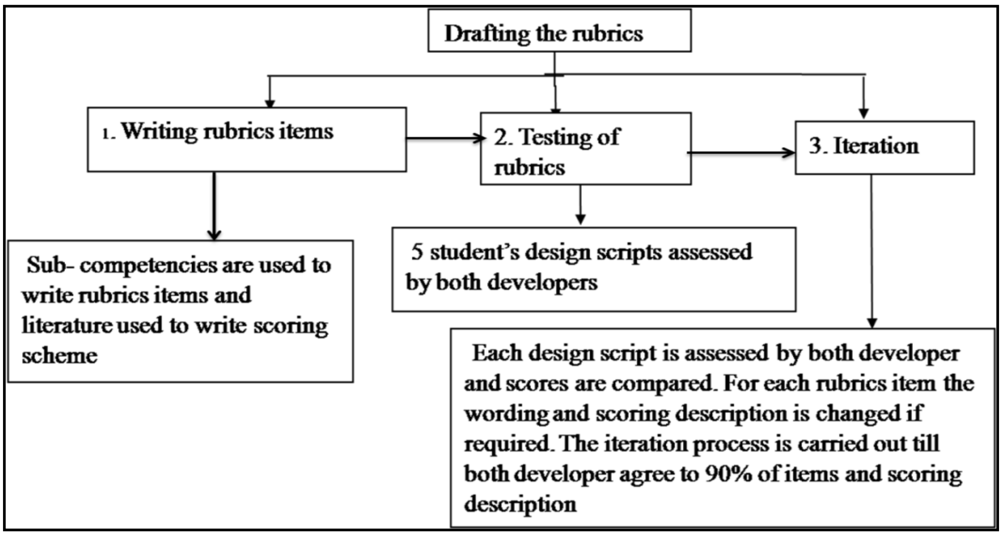


Fig. 4.3. Flowchart for writing rubrics

An example of a rubrics item from the structure open problem competency, before and after discussion, is shown in Table 4.3. Rubrics items and scoring descriptions were modified through such an iterative process of scoring sample solutions and discussing agreement, till a 90% agreement was reached.

Table 4.3. Revision of rubrics item from structure open problem competency

Design sub-competency	**Rubrics item, first draft before discussion**	**Rubrics item revised after application to solution and discussion of scores**
Is able to use specifications to structure problem	Target performance (level 3) All specifications applied to structure the given Problem	Target performance (level 3) All specifications are used to take decisions to structure problem. All interconnections of the system are identified based on given and identified specifications such as the decision related to requirement of two stages based on gain requirement is identified.

The complete rubrics items and its scoring description for "Structure open problem" are shown in Table 4.4. The rubrics items will be henceforth referred as SOP1, SOP2, SOP3, and SOP4. The complete rubrics for all design competencies are attached in the table A1.2 of Appendix I.

Table 4.4. Rubrics items for structure open problem (SOP) competency

Design sub-competency	**Target performance**	**Needs improvement**	**Inadequate**	**Missing**
Is able to extract required relevant specifications in detail from given open ended problem	All relevant visible and hidden specifications are identified in detail and interpreted accurately. No irrelevant specifications identified.	An attempt is made to identify specification Most of them identified but few hidden ones missing or needs more interpretation	An attempt is made but specifications identified are most of them are wrong or irrelevant or incomplete.	No attempt is made to extract specifications
Is able to structure open problem using specifications	All specifications are used to take decisions to structure problem. All interconnections of the system are identified based on given and identified specifications.	An attempt is made to use specifications correctly but some minor specifications are not used for decision making such as which active device should be connected first is not considered while structuring the problem	An attempt is made to use specifications but specifications are wrongly applied or some required specifications not applied to make decisions regarding the problem.	No attempt is made to use specification or identify structure
Is able to sequence the design steps based on specifications	All major and minor design steps are identified and sequenced correctly based on specifications	Most of the designs steps are identified and are sequenced correctly. Few minor steps are missing or not sequenced correctly.	Design steps are not sequenced at all or not based on specifications.	No attempt is made to write design steps.
Is able to write structured design problem statement	Problem statement is written clearly including all details related to devices, devices structures, and design steps.	Problem statement is written clearly but few minor details are missing.	Problem statement is not written clearly but scattered information is available	No attempt to write word statement. or no scattered information is available

4.4. Establishing validity and reliability of rubrics

4.4.1. Types of validity and reliability

For any assessment instrument, it is important that the scores and their interpretations should be valid (Cronbach & Meehl, 1955; Messick & Linn, 1989) and reliable (APA, 1999). The main purpose of validity is "accumulation of evidence to provide sound scientific base for score interpretation". Since assessment purposes may differ, the instrument developed for one purpose may not be valid for another purpose and the instrument should be validated for the intended purpose (Messick & Linn, 1989; APA, 1999; Docktor, 2009). Since the goal of the rubrics we developed is to assess students' engineering design competencies, the interpretation of the score should accurately reflect the acquisition of these competencies by students. In our study, we establish validity in the context of design problems in electronics. Our intent is that the rubrics will be applicable to assess all types of problem from this domain.

Validity of an instrument needs to be established from multiple perspectives, for example, the instrument should assess what it intended to assess, and it should cover the intended domain completely. Validity is defined as "Degree at which instrument measures what it intends to measure" (Cohen et.al, 2000). For rubrics, validity refers to "degree to which score interpretations are supported by empirical evidence and theory" (Docktor, 2009). Three types of validity mentioned (APA, 1999; Messick & Linn, 1989) are content, construct and criterion. To establish the validity of the rubrics, we first identified the purpose of our proposed instrument and its application area. Further, we identified the expected users of our instrument to establish the reliability between different users. We found that rubrics need to fulfil following objectives:

- The items of rubrics should able to assess design competency undertaken by designer.
- Rubrics scores allotted by different raters to same problem should be consistent.

To interpret definitions of the different types of validity to our objectives, we applied the definitions of its different types to rubrics. Table 4.5 shows a summary of the validity and reliability studies we performed. It includes: the types of validity from a traditional perspective (Cohen, 2000; Kerlinger, 1973; Docktor, 2009) its interpretation to rubrics, why it is of importance for our instrument, and its operationalization in our study.

Table 4.5. Types of validity, and its application to engineering design competency rubrics

Type of validity (traditional definition)	**Interpretation for rubrics**	**Relevance**	**Application to our instrument**	**Sources of evidence**
Content validity Representative-ness of the content of the measuring instrument. The instrument should cover all the claimed area.	Content for rubrics means the wording of item, which should assess student's knowledge of content area and cover the domain area (Docktor, 2009).	The rubrics items should cover all the categories of design competencies applied by designer in the domain of analog electronics	Check if the wording of our rubrics items covers all the design competencies of the students in the domain and if each competency is adequately assessed using rubrics items.	Experts' judgment about the content of rubrics items via interviews. Experts are from analog circuit domain with experience of conducting design based courses.
Construct validity Construct validity refers to the degree to which inferences can legitimately be made from the operationalization in the study to the theoretical constructs on which that operationalization was based.	The construct is internal process being measured, and validity is consistency between the assessment's intended process and that actually followed by the student.	The items of rubrics should also able to assess design thinking process undertaken by designer.	1) Response process: to what extent rubrics assess design thinking process actually engaged in by individuals. 2) Criterion validity: to what extent is there consistency between rubrics scores and scores on final design product evaluated by a teacher?	Students' and experts' solutions to open design problem are assessed using rubrics to determine the range of competencies used. Interviews are conducted to determine students' actual process. 2) Students' design solutions are assessed by independent method
Generalizability Applicability of the assessment across different tasks, populations, situations, or times.	The extent to which the rubric is applicable to multiple populations and contexts, including different student from different topics and problem features (Docktor, 2009).	Rubrics should be applicable to expert solutions as well as novice solutions and be able to distinguish them. Rubrics should able to assess different types of problem from the domain of applicability.	Rubrics applicability to different topics and student solutions from different courses and levels.	Solutions to design problems from books for various topics, as well students' solution from different levels are assessed using rubrics.
Inter-rater reliability	The agreement of scores from multiple raters (Docktor, 2009).	Rubrics scores allotted by different raters to same problem should be consistent	To what extent rubrics scores allotted by different raters are consistent.	Four raters assessed design solutions written by students and agreement is calculated

4.4.2. Content validity

To establish content validity, we discussed rubrics items and scoring description with experts in the domain. Our sample consisted of four experts, who were faculty members in engineering colleges and institutes with 5-15 years' experience. The experts had experience of designing and conducting design based courses in electronics for undergraduate and graduate populations. The experts were also familiar with rubrics and can apply it for assessing design solutions written by students. The following points related to rubrics were addressed:

- For each identified design competency are the measurable units (sub-competencies) sufficient and covers all the aspects of major competencies?
- Whether the wording of rubrics items describes accurate measurable unit?
- Whether target performance sufficiently describes expected outcome?

Each expert was interviewed one by one. After getting the responses to our rubrics by one expert, we modified the rubrics as per their suggestion, and asked them to re-validate our rubrics. Once one expert had approved the validity of the rubrics, we approached the next expert with the new draft. We iterated this process with all experts, till no change was suggested.

Overall, most rubrics items and the wordings were found to be sufficient and necessary to assess identified design competencies. The experts agreed that identified competencies are sufficiently covering broad area of design problems in electronics domain. For Expert1, there was 100% agreement for rubrics items and scoring scheme for convergent and divergent thinking design competency, but he suggested modification in information gathering competency.

When we discussed with Expert 2, there were minor changes in design competency items for multiple representation and information gathering. We discussed with Expert 3 the revised version and got minor suggestion in think divergent design competency. When we discussed with Expert 4, there were no changes in the rubrics items or scoring. We used this rubrics draft as final draft to establish construct validity. Table 4.6 shows a summary of what changes were made as per suggestion by experts. We note that there were fewer changes suggested with each new expert, and there was saturation in the process.

Table 4.6. Changes in rubrics items

Design competencies (original)	Rubrics items changed as per Expert1	Rubrics items changed as per Expert2	Rubrics items changed as per Expert3	Rubrics items changed as per Expert4
MR	MR2-	No change	No change	No change
IG	IG1 IG2	IG1 IG2	No change	No change
SOP	SOP1 SOP3	SOP3	No change	No change
DIV	DIV1 DIV3	No change	DIV1	no change
CONV	No change	No change	CON3-	no change

4.4.3. Construct validity - Response Process

Construct validity is first interpreted as a response process - to what extent does the instrument (rubrics) assess design thinking process actually engaged in by individuals (Docktor, 2009). To demonstrate construct validity, we scored design solutions of experts for the same design question. If our rubrics indeed have construct validity, we expect that:

i) Experts' solutions will score higher than students and most scores are likely to be at the Target Performance level.

ii) In students' solutions, we will see a range of scores in all rubric items reflecting students' differing abilities.

We assessed design solutions of second year students of Electronics and telecommunication. Our sample consisted of 20 students who solved a problem to design an amplifier. Some students have been successful in solving the problem and getting a final design solution that worked. Our assumption is that successful students would have used most design competencies in order to arrive at their solution. It is expected that their written solutions reflect the design competencies applied while writing solutions. If we assess these solutions using rubrics we should be able to see non-zero rubrics score.

We assessed solutions using rubrics and found that there is evidence of all the competency categories in students' written solutions. Fig. 4.4 shows plot of rubrics scores for student solutions. The scores 0, 1, 2, and 3 (horizontal axis) refer to the four levels in our rubrics: Missing, Inadequate, Needs improvement and Target Performance. Existence of the range of rubrics scores, that is, non-zero and varied scores for all competencies indicated the response process was assessed by rubrics. If rubrics were not valid we would not have obtained a range of scores for all the categories. The exception was the divergent thinking competency, which had a zero score for all solutions. Further interviews with students determined that none had written their efforts at divergent thinking in their solution, even though some had made such effort.

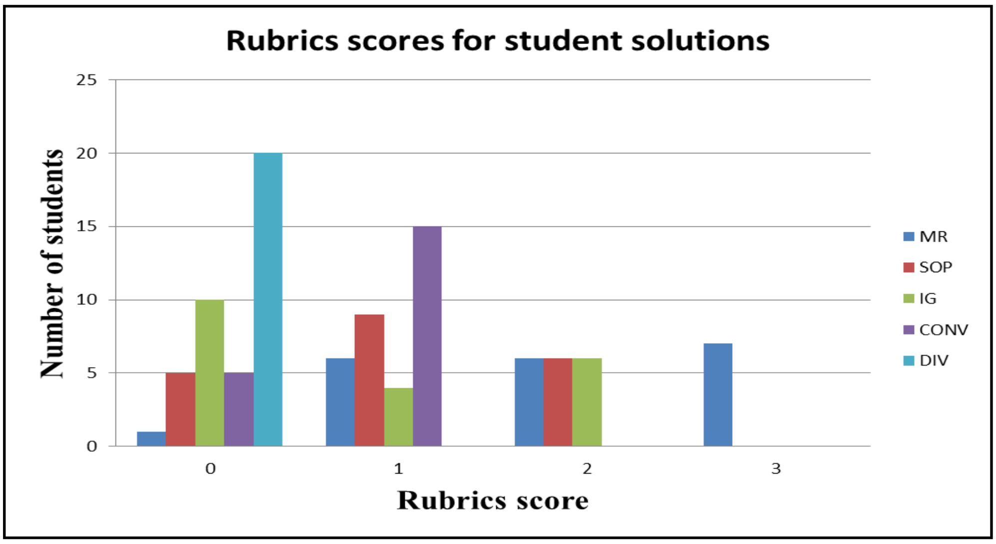


Fig. 4.4. Rubrics scores of students' solutions

Experts' solutions using rubrics were assessed (Fig. 4.5). Four faculty members with teaching experience of more than 8 years solved one design problem each from set of problems solved by students. We found that the competency categories show non zero rubrics score and also the scores are at higher side (mostly level 3) compared to scores obtained by students, indicating that rubrics can discriminate between expert and novice solutions. For DIV score of 1 we found that in experts' written solutions multiple solutions and analysis was not mentioned but subsequent interviews revealed that multiple solutions are possible and one need to consider and analyse them, but also mentioned that problem question should give prompts for this competency otherwise students may not consider multiple solution options.

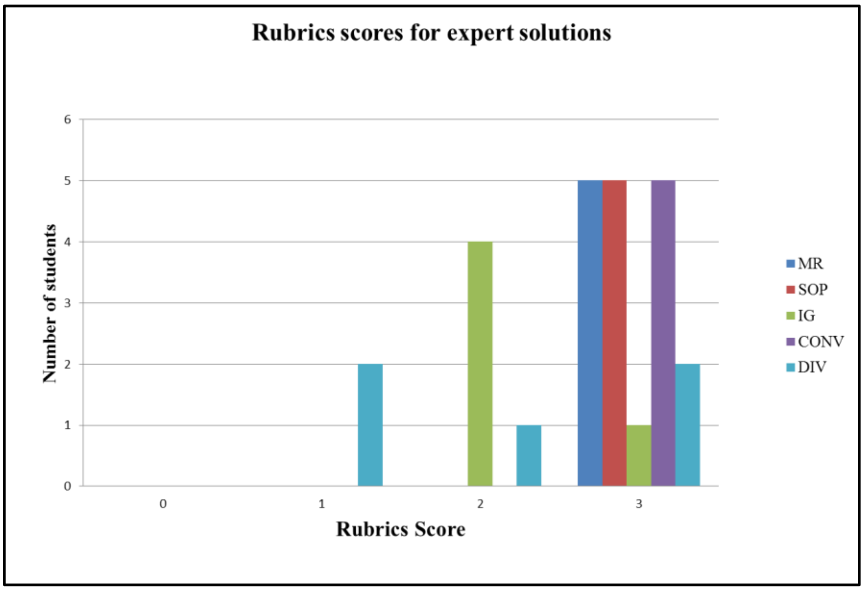


Fig. 4.5. Rubrics scores of experts' solution

4.4.4. Construct validity – Criterion validity

To further support construct validity we evaluated students' design solutions by an independent criterion. These solutions were assessed by the course instructor using the grading criteria they had used in the course for the past several years such as application of concepts, appropriate selection of formula and its application to calculate component values. Three faculty members from different colleges with more than 5 years teaching experience allotted grades to students' design solutions. Each assessed 20 design solutions of amplifier design problem. The same solutions were scored using our rubrics by the researchers. We then examined the similarity between instructors' grades and rubrics scores.

The consistency between the scores is compared using statistical tests as follows:

1) We plotted the average design grade allotted for every student's solution by the three instructors versus the average rubrics scores over all categories. The scatter plot (Fig. 4.6.) indicates that the variation in design grade with respect to rubrics score is 82% (R^2), indicating consistency between the two scoring methods.

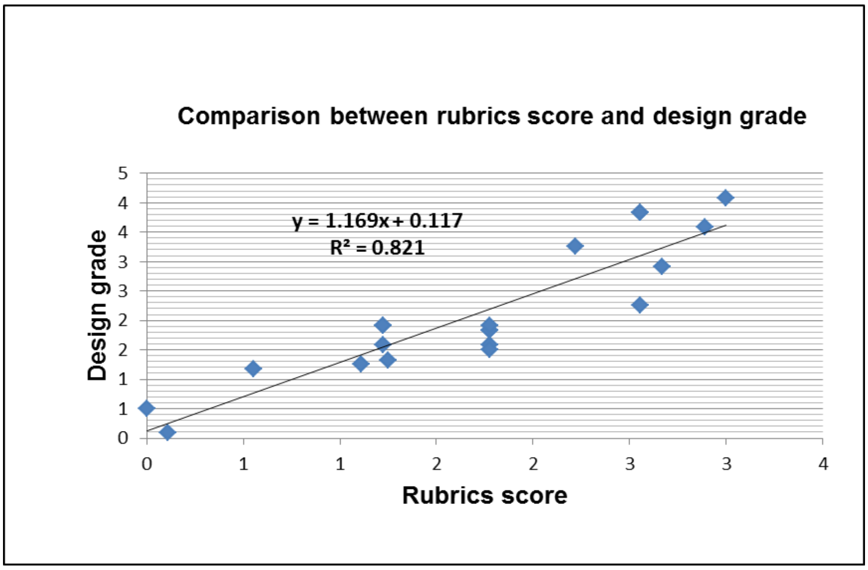


Fig. 4.6. Relation between design grade and rubrics scores

2) The correlation coefficient between the average design grade allotted by the three instructors, and the rubrics scores for each design competency were determined. The correlation coefficients in table 4.7 shows that the rubrics scores for each design competency are statistically significantly correlated ($p<0.01$) with the average design grades allotted by design instructor, establishing the criterion validity for our rubrics. We found zero score for DIV competency in student's solution and thus could not calculate correlation for DIV competency.

Table 4.7. Correlation between design grade and competency scores

Design competency	**MR**	**SOP**	**IG**	**CONV**
Correlation coefficient (Pearson) with average grade by instructor	.782*	.616*	.666*	.786*

(*significant at p=0.01)

4.4.5 Generalizability

Ten solutions from design text books were scored on different topics covering range of design problems from analog electronics circuits like power amplifier design, waveform generator, and wideband amplifier. Textbook solutions are expected to reflect competencies applied by experts to solve open design problems. We found high rubrics scores (2 or 3) for all the competencies for all the solutions from the textbook (Fig. 4.7). We can conclude that rubrics are applicable to different topics in the chosen domain of analog electronics.

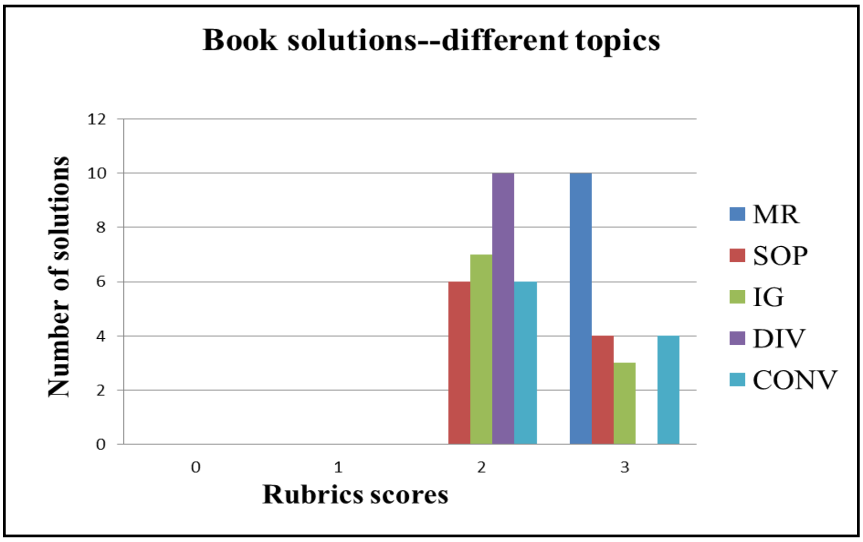


Fig. 4.7. Rubrics score for different topics

4.4.6 Reliability

An important purpose of assessment instruments is that they should be uniformly interpreted and applied by different raters. We thus carried out reliability of rubrics with multiple raters. Our sample consisted of three raters, all of whom are familiar with the domain of analog electronics, and two of whom (Rater1 & Rater2) were doctoral students in education, and were hence familiar with using rubrics as assessment instruments. However, none of them were familiar with the rubrics in this study before this exercise. The third rater, Rater 3, is an engineering college faculty member with experience teaching design courses, but with no formal training in assessment techniques before this exercise.

The procedure was as follows: A rater scored four solutions, one-by-one, to a problem on amplifier design by 2nd year electronics engineering students. Simultaneously, the researcher scored the same problem. After scoring a solution, there was a discussion between the rater and the researcher on the agreement between their scores, before scoring the next solution. If there was a discrepancy, the researcher clarified the meaning of a rubrics item or scoring description, and shared her reasons for giving a particular score based on the rubrics scoring description. The discussion played the role of training the rater in using the rubrics. This procedure was repeated by the researcher with each of the three raters. A similar procedure has been recommended (Etkina et.al, 2006; Docktor, 2009) to train raters to use rubrics.

We represent the result of reliability testing as: i) a comparative table which indicates the percent agreement for each design competency between the rater and the researcher between first and fourth solution ii) progression in Kappa value as training progresses. The Kappa value indicates the statistical significance of the agreement.

We initially calculated agreement between raters and researchers individually after scoring four solutions and then calculated average agreement. We found that the score agreement was lower initially. Training was given in the form of discussion of the reasons for scores using rubrics, and then the next set of solutions was scored. The statistical significance of the agreement was kappa=0.88. Table 4.8 shows agreement of all competencies and average overall agreement before and after training.

Table 4.8. Average Agreement of rubrics scores (statistical significance kappa) for all raters

Competency category	**%perfect agreement((before) (Average)**	**%perfect agreement (after)(Average)**	**Quadratic weighted Kappa**
SOP	34	75	0.61
MR	55	94	0.95
IG	21	83	0.83
DIV	100	100	1.00
CONV	41	85	0.80
Overall	51	90	0.89

Fig. 4.8 indicates improved kappa value as training progresses for all three raters. We found that for raters who had a background in educational technology, the kappa value converged after 2 or 3 iterations while Rater3, four iterations were required to converge to Kappa value.

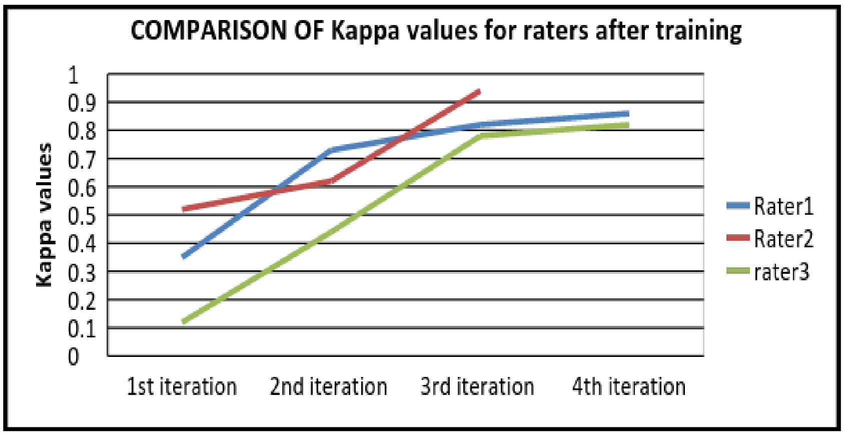


Fig. 4.8. Variation in Kappa for three raters as training progresses

4.5. Implementation of rubrics and usability

4.5.1. Rubrics used to assess student design solutions

This section illustrates the use of rubrics to score students" design solution to the following problem: "You are designing a project for class project exhibition, in your project you want to display signal which has strength of 10mV, but the display system demands minimum 0.5 V signal. The frequency range of the signal is 100Hz to 800 KHz. Your signal source may overload amplifier if impedance is less than 120K. Design an amplifier for your project."

Fig. 4.9 shows part of written solutions (Structure Open problem competency) of student who was not able to complete design task successfully. Fig. 4.10 shows part of written solution of student who was able to complete design task successfully. In both figures circled part of solution indicates statements showing existence of sub-competency. We referred Table 4.4 to score these solutions and boxes represent mapped sub-competency and reason for scoring respectively.

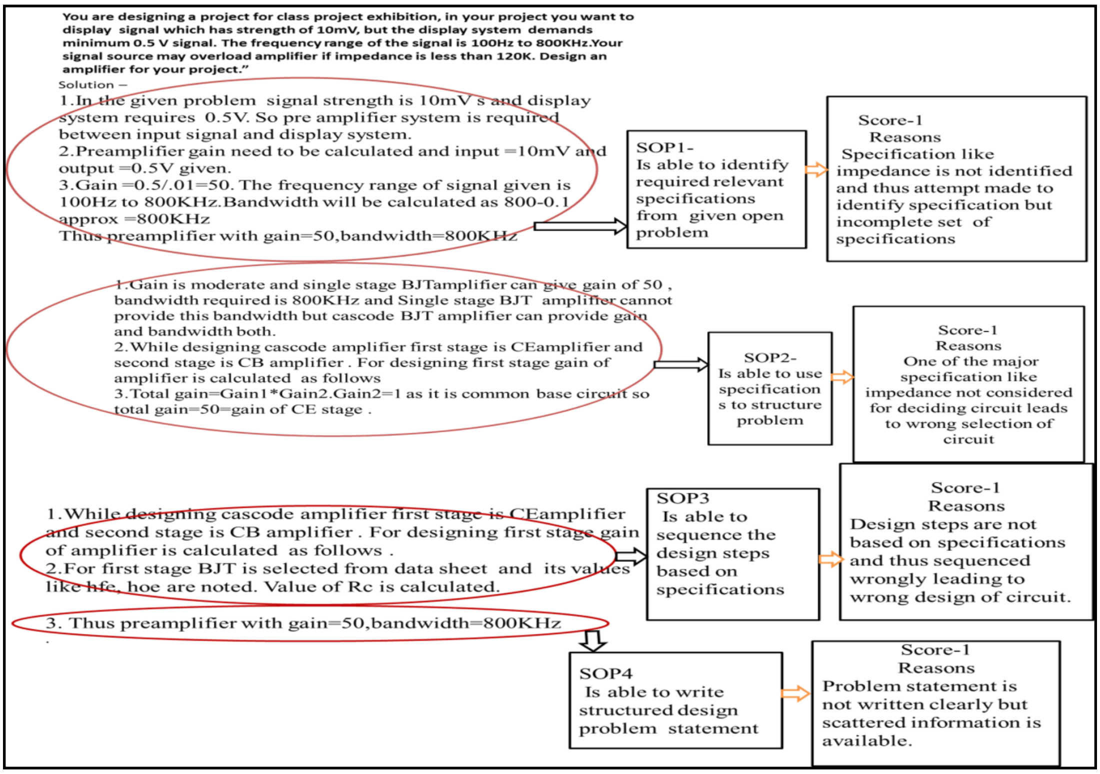


Fig. 4.9. Rubrics scores of an unsuccessful design ("poor solution")

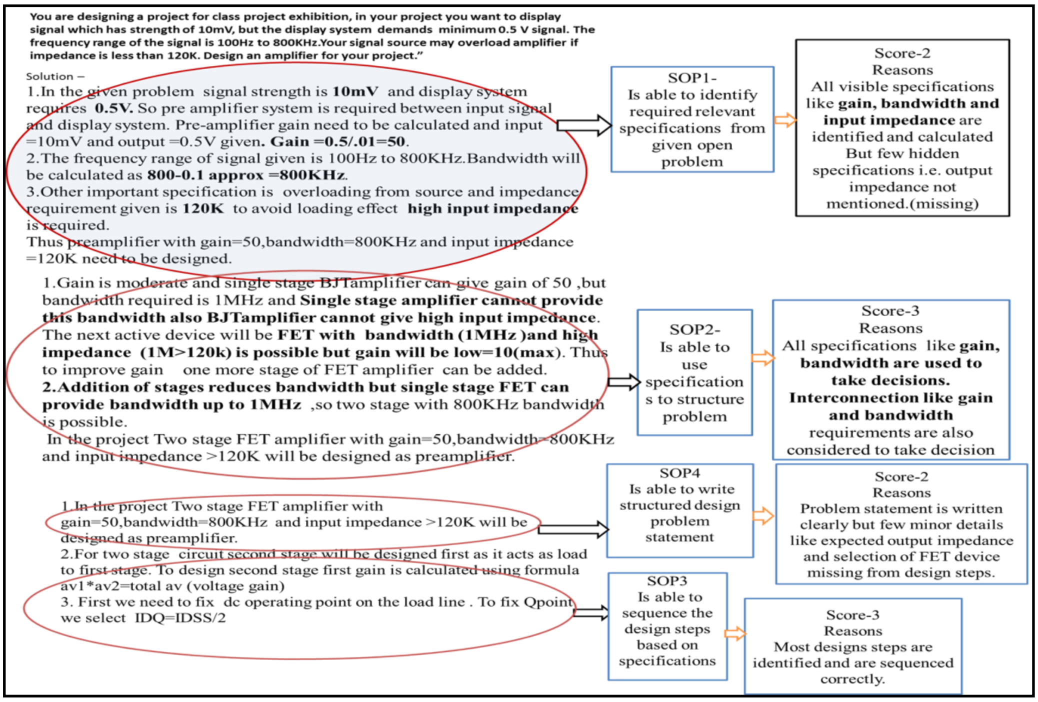


Fig. 4.10. Rubrics scores of a successful design ("good solution")

4.5.2. Usability of rubrics by teachers

The System Usability Scale (SUS) (Bangor, 2009), which is a reliable tool for measuring the usability of a wide range of products was applied to determine the usability of the rubrics by its primary users, i.e. electronics design course instructors. The survey consists of a 10-item questionnaire with five response options ranging from Strongly Agree to Strongly Disagree. A sample item is: "I thought the rubrics were easy to use". Seven instructors of an electronics circuit design course used rubrics to assess students' written solutions to a design problem. They then filled the SUS. The average SUS score was found to be 72, which is reported as a "good" usability score (a score above 68 falls in the category "product has good usability") (Bangor, 2009).

4.6. Interpretation of rubrics scores: competency achievement

The approach taken in this thesis for assessment of engineering design thinking skill is to identify the competencies that constitute the thinking skill, and then operationalize each competency in terms of measurable sub-competencies, which are assessed by the rubrics. We assess the development of learners' engineering design thinking skill by assessing their attainment of design competencies – Structure Open Problem, Multiple Representations, Information Gathering, Divergent Thinking and Convergent thinking. The attainment of the above engineering competencies is evaluated by learners' performance of sub-competencies (via rubrics scores) that make up that competency.

Each of the identified competencies is independently important in the development engineering design thinking skill. Structure Open Problem competency is essential as it is the first step of design process. A substantial part of design activity is devoted to structuring and formulation of problem (Cross, 2007) and poor structuring of problem leads to poor design of artefacts (Atman, 1999). Multiple Representations is an integral part of design process as accurate representation of circuit diagrams, blocks or process will help students to design appropriate product. While designing solutions students need to think of divergent possible solutions based on specifications, implementation possibilities and also able to converge the ideas based on implementation possibilities. Similarly students should select appropriate information source as well as information. Structure Open Problem is seen most prominently at the start of design, while Multiple Representations and Information Gathering support SOP. On the other hand, Convergent and Divergent Thinking appear throughout the design process. Design thinking is thus a non-linear process involving the need for all competencies identified in Table 4.1.

Our approach was not to find a mathematical formula for engineering design thinking skill achievement, but to track students' progress of individual competencies and their constituent sub-competencies. This approach is especially recommended for providing formative assessment for students. It has been shown that giving students a final total grade is not useful for their learning and skill improvement (Shepard, 2000). In case of assessment of complex performance task it is important to give students specific feedback on target level performance and immediate levels with each level is highly descriptive and specific. Thus we developed descriptive rubrics for each sub-competency assessment but do not assign marks.

Similarly, for every main competency there are few sub-competencies, for each of which we defined the performance levels. While some sub-competencies may be easier for students to attain than others, we show that in order for a student to achieve a certain main competency, the attainment of each sub-competency is necessary. One example of Structure Open Problem (SOP) competence achievement through its sub-competencies, and the role of each sub-competency is described below.

The first sub-competency identified in Structure Open Problem competency is 'identification of specifications' (SOP1). From the given open problem, if students are not able to identify all relevant specifications the decisions related to circuit design will be wrong. For example, in given application amplifier circuit to be designed for specifications like gain, bandwidth and impedance, students may have identified gain alone as the important specification. They may have calculated gain and then decided the components and designed the circuit. The circuit thus selected and designed, does not include bandwidth specification and thus not suitable for the given application. Goals of design will not be clear to them and they land up designing irrelevant circuit not applicable to given application.

The second sub-competency of SOP, 'deciding structure using specifications' (SOP2) is also equally important. Even though all relevant specifications are identified students, should be able to decide which circuits can satisfy all specification. It becomes especially important if there is any inverse or direct relationship between different specifications and how will they play role in circuit decision. For example, in amplifier design gain and bandwidth are inversely related. Depending on values of required gain and bandwidth students should decide number of stages and types of configurations. So if students did not understand relation between two specifications then they will select the wrong circuit. So this sub-competency allows students to connect specifications to the circuit designed, hence has direct impact on final design of students.

The third sub-competency of SOP is ‘selecting design steps in sequence’ (SOP3). This sub-competency contributes to decisions such as which is the first part of the circuit to be designed, and how it may lead to design of next part. Sometime the sequence of design steps is crucial, as the design calculations are dependent on this sequence. For example, if students are designing multistage amplifier they have to design second stage first, as second stage acts as load to first stage.

The fourth sub-competency of SOP is the key sub-competency in being able to successfully structure the open problem, ‘write structured design problem statement’ (SOP4). SOP4 assumes the attainment of all above sub-competencies (SOP1, SOP2, and SOP3) and expects students to synthesize all the above in order to decide how to structure the open problem.

Further to get insight into how rubrics scores for each sub-competency is related to its main competency, we statistically analysed the correlation between sub-competency scores of Structure Open Problem, achieved by students in their design solutions.

Table 4.9. Correlation between SOP sub-competencies

Sub-competencies	**SOP1**	**SOP2**	**SOP3**	**SOP4**	**SOP(main)**
SOP1	1	0.9*	0.3	0.48*	0.83*
SOP2		1	0.5*	0.63*	0.93*
SOP3			1	0.64*	0.72*
SOP4				1	0.78*

(*significant at p=0.05)

Students solutions (N=20) to design problems were scored using the SOP rubrics. We then calculated correlation coefficient between each sub-competency and correlation with main competency score. Main competency score is calculated as average of all sub-competency scores. Table 4.9 shows the correlation for "Structure Open Problem (SOP)" and its constituent sub-competencies.

All sub-competency scores are positively correlated with SOP competence score which further establishes need of developing all sub-competencies independently to attain SOP competence level. It was also found that sub-competencies SOP1, SOP2, SOP3 are significantly correlated with SOP4. This indicates that students will be able to write structured problem statement accurately provided they have attained competence in other three sub-competencies. SOP2 and SOP3 are significantly correlated but there was no significant correlation found between SOP1 and SOP3.

Thus we concluded that development of each sub-competency is essential to develop main competency and henceforth we calculated contribution of sub-competency scores independently.

4.7. Summary

This chapter explores the process of operationalization of engineering design competencies. The process began by identifying specific measurable units (sub-competencies) of design competencies. The performance levels of sub-competencies were decided using assessment rubrics. All the competencies need to be developed independently and are essential to claim development of engineering design thinking skill. The process of the development and validation of rubrics to assess engineering design competencies is described in detail in this chapter. The validity and reliability of the rubrics is established using a variety of data collection and analysis methods. It was found that the rubrics developed in this study reflect the competencies used by students in the design process. The rubrics accurately differentiate the performance of novices and experts, and are consistent with independent methods of assessment of design competencies. The rubrics are applicable to a variety of problems in the domain of analog electronics and are found to be applicable and usable by practicing instructors.

The primary contribution to the thesis from this chapter is the development of a research-based validated instrument to assess the development of engineering design competencies. While the empirical results focus on the application of the instrument to analog electronics circuit design, we surmise that the rubrics can be directly applied to nearby domains such as digital electronics and power electronics, as these domains also need specifications and its application in design of problems. Competencies such as structure open problem, information gathering, convergent and divergent thinking are typical to design problems in most of the engineering topics even from non-electrical engineering domains (computer science, civil, mechanical). Hence we propose that competencies and sub-competencies identified in this study are applicable more generally. This claim need further testing.

In addition, the target performance level defined by rubrics for a particular sub-competency provides outcomes for the learning activities in the TEL environment that will be developed as the intervention for students' development of engineering design competencies (TELE-EDesC). The next chapter focuses on the identification of instructional strategies and development of learning activities in TELE-EDesC to achieve competency based learning outcomes, thereby addressing the final step in the backward design approach. We scope our work to SOP competency and its learning outcomes to design the TELE-EDesC learning activities.

Chapter 5

Development of TELE-EDesC Learning Environment

This chapter reports the development of the technology enhanced learning (TEL) environment we developed for engineering design competency. This is the last step of backward design approach used in the Design Prototype phase of Education Design Research, the overall research method used in this thesis (Chapter 3). After implementing the first two steps of backward design - deciding the learning outcomes and assessment measures for engineering design competencies (Chapter 4), the next step is to develop and test the TEL environment, that we call TELE-EDesC (pronounced 'Tele-desk'). A review of teaching-learning strategies recommended for broad engineering design thinking (Chapter 2) shows that the solution must be a guided exploratory environment. Further, technology affordance allows the design of complex tasks in which abstract ideas can be explored to promote the necessary cognitive processes (Reiser, 2004). Further it is strongly stated that technology affordances support guided exploration. Hence TELE-EDesC is one such guided exploratory environment.

The main research question (RQ) addressed in this thesis is "RQ2: How to develop a TEL environment to teach engineering design competencies?" (Chapters 2 & 3 give an overview of the RQs in the thesis). This research question is answered by developing TELE-EDesC modules and a pedagogical framework to design a TEL environment for engineering design competencies. Section 5.1 describes the research method applied to answer the research question. Section 5.2-5.4 describes the process of TELE-EDesC development. The pedagogical framework to design a TEL environment for structure open problem (SOP) competency emerges from this development process (Section 5.5). Based on the framework, TELE-EDesC modules are designed for SOP competency in topics from analog electronics domain. Section 5.6 describes an example of content development of TELE-EDesC for SOP competency and provides guidelines for a user to develop TELE-EDesC modules for SOP competency in different topics.

5.1. Research method

In Chapter 3, we described the overall research method that is used in this thesis, Education Design Research, and its various phases. In Chapter 4, we focused on the initial steps of the Design Prototype phase implemented via backward design approach. Chapter 4 identified measurable units for each engineering design competency in terms of sub-competencies and desired target performance levels. This led to expected learning outcomes for each competency and assessment instruments. This chapter focuses on the last step, the design of the teaching-learning intervention.

In order to develop the intervention (TELE-EDesC), we first studied actions of experts while they engaged in the design thinking process. We identified experts' actions to achieve the above learning outcomes by carrying out a content analysis of experts' solutions to design problems. This qualitative study indicated the need for metacognitive processes (Brown & Palincsar, 1982; Pressley & McCormick, 1995; Biswas et al., 2013) to be executed for attainment of design competencies. The learning activities in TELE-EDesC were then developed to trigger the metacognitive processes obtained from qualitative analysis of experts' design solutions. A focused analysis of literature was carried out to find recommended instructional strategies to trigger metacognitive processes. In addition, instructional design principles (Moreno & Mayer, 2007) and multimedia principles (Mayer, 2005) were surveyed and applied to develop learning activities with the technology-enhanced environment of TELE-EDesC (Fig. 5.1).

In Chapter 4, engineering design thinking skill was operationalized into competencies and sub-competencies, and assessment rubrics were developed for all competencies. One of those competencies, Structure Open Problem, is chosen to develop TELE-EDesC learning modules. Structure Open Problem competency was chosen since it is the first step of the design process and a substantial part of design activity is devoted to structuring and formulation of problem. It is important for students to attain this competency well, since it has been seen that the design of good quality artefacts depends on how well the problem is structured (Atman, 1999; Cross, 2007). (In Chapter 8, we attempt to expand the scope of this work and suggest the design of TELE-EDesC modules for other engineering design competencies).

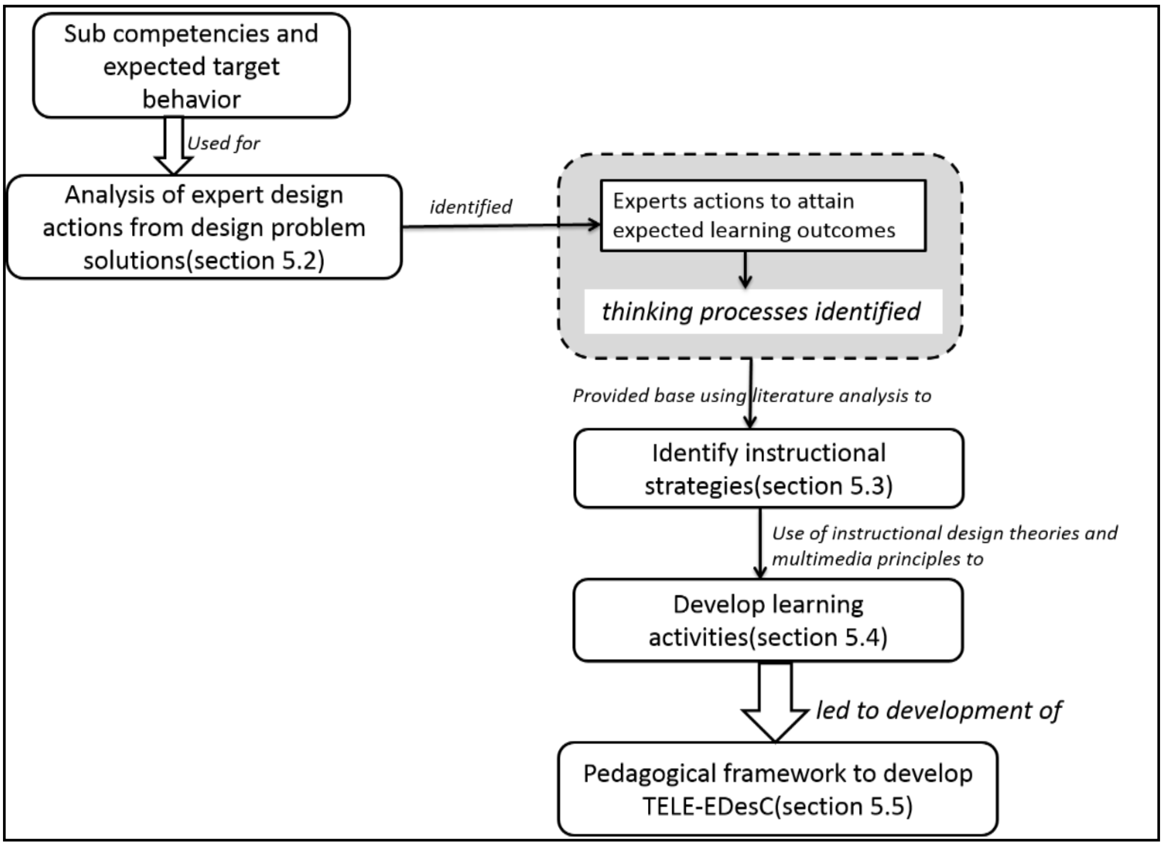


Fig. 5.1. Research method for TELE-EDesC development (reproduced from Chapter 3)

In addition, the type of design problems addressed by TELE-EDesC is currently scoped to 'Innovative' design problems, (Brown & Chandrasekaran, 1989). In such problems, students need to take decisions based on their prior content knowledge and available information. In this type of problem real life problem is given, type of circuits like amplifier filter etc. are mentioned but designer need to extract all relevant specifications for given application and decide which type of filter or amplifier is suitable in the given application.

5.2. Analysis of experts' design solution for SOP competency

Sub-competencies and target performance (Chapter 4) of SOP are applied to define learning outcomes for each sub-competency (Table 5.1).

Table 5.1. Learning outcomes for sub-competencies

Sub-competency	**Expected learning outcome (Students will be able to)**
SOP1: Identification of specifications	1. Identify all the relevant visible and hidden specifications in detail. 2. Interpret specifications.
SOP2: Use of specifications	1. Apply all the relevant specifications to take decisions to structure problem. 2. Decide all interconnections of the system based on given and identified specifications.
SOP3: Decide design steps	1. All the decision steps identified. 2. All steps sequenced correctly based on specifications.
SOP4: Write structured statement	1.Write problem statement by systematically integrating specifications, decision steps, devices, structures etc.

Five experts from Analog electronics circuit domain were asked to write solutions to an open design problem in amplifier design topic. Experts' solutions to these design problems were analysed to know their design thinking actions to achieve the learning outcomes. Fig. 5.2 shows the example of content analysis of an expert's design actions sub-competency wise. First, all the relevant actions under sub-competencies were grouped together. Codes were assigned for each relevant action. For example, consider the design statement "*Calculate gain of the amplifier as Voltage gain=1V/1mV=1000. The first specification is voltage gain of the amplifier is 1000".* This action falls under SOP1 sub-competency. The code assigned to this action is 'Apply Concepts'. There are number of codes that emerge from the actions taken by experts to achieve learning outcomes for each sub-competency. When these codes are examined it was found that some of the actions can be categorised under common heading. For example, for "*SOP1-Identification of specifications"* the action of identifying visible and hidden specifications, and the action of calculating appropriate values of relevant specifications were performed by applying and integrating various concepts from the domain.

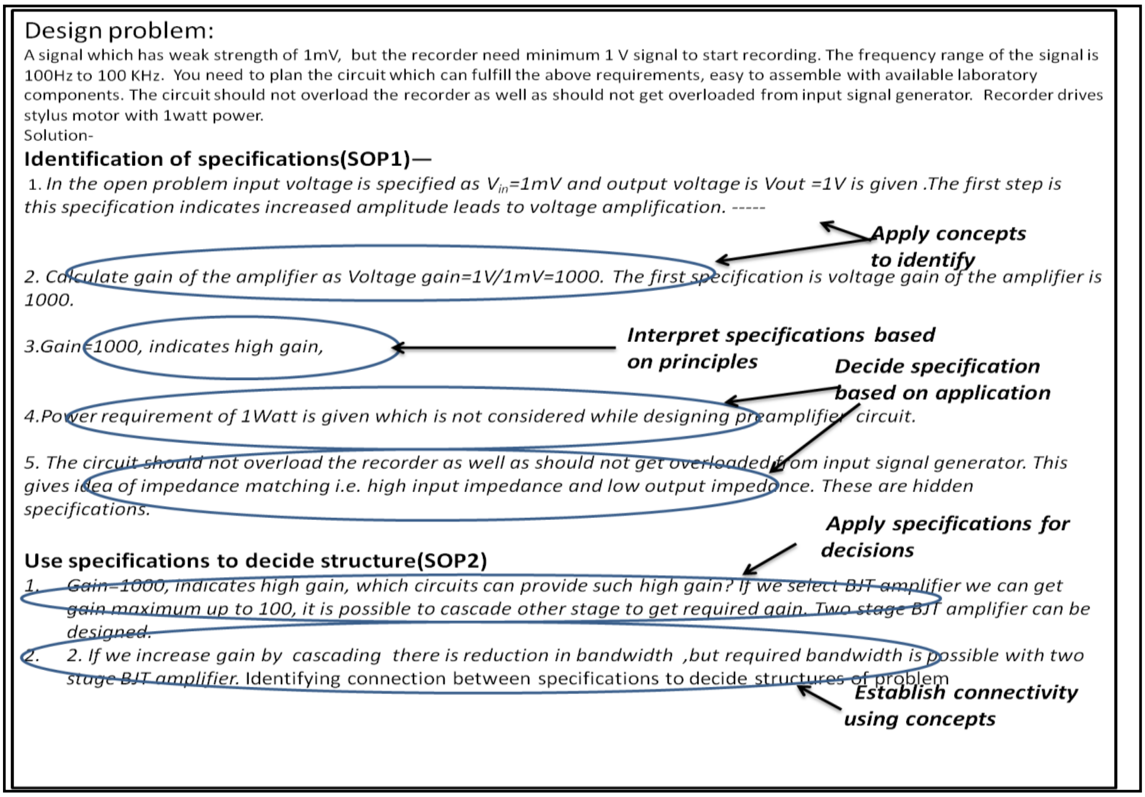


Fig. 5.2. Example of content analysis of an expert's design actions, sub-competency wise.

For each sub-competency of SOP such types of actions were frequently seen. Common actions were clubbed together into category. For example, for SOP1 sub-competency, students need to decide relevant specifications, while for SOP2 sub-competency; students should be able to decide appropriate circuit for identified specification. Both these tasks require decision in different situations. For both these competencies decision task was clubbed into decision making category. Categories emerged showed similarity with the design thinking processes identified from literature in Section 2.2, Chapter 2. These categories are found to indicate the metacognition processes (Brown & Palincsar, 1982; Biswas et.al, 2013) to be applied to attain competence in SOP. We thus referred these categories as *metacognitive processes*. Table 5.2 shows the codes that emerged for learning outcomes, and the categorisation of these codes in terms of metacognitive processes.

Table 5.2. Codes and categories for SOP learning outcomes

Sub-competency	Learning outcomes	Codes (experts actions)	Categories (metacognitive processes)
SOP1- Identification of specifications	Identify all the relevant visible and hidden specifications in detail.	1. Use of concepts or principles for identification.	Concept Integration
		2. Decide appropriate specification	Decision Making
	Interpret specifications	3. Interpret specification using known concepts	Concept integration
SOP2- Use of specifications	Apply all the specifications to take decisions to structure problem.	1. Apply specifications to take decisions.	Decision making
	Decide all interconnections of the system based on given and identified specifications	2. Identify connection between specifications to decide structures of problem	Concept integration and decision making
		3. Apply integrated set of specifications to take decisions	Decision making
SOP3- Implement Sequential of design steps	All the decision steps identified.	1. Link decision steps to each other	Concept integration
	All steps sequenced correctly based on specifications.	2.Decide sequence of decision steps	Decision making
SOP4- Write structured statements	Write problem statement by systematically integrating specifications, decision steps, devices, structures.	Synthesis of all above tasks which involves recalling of concepts, deciding the structures, applying information and integrating process.	Synthesis

The main metacognitive processes identified from experts' design solutions to attain SOP competency are decision making, concept integration and synthesis. Our goal is that the learning activities in TELE-EDesC modules should be able to trigger these metacognitive processes by incorporating appropriate instructional strategies (Zimmerman, 2006; Xun & Land, 2004; Linn et al., 2003). In the next section (5.3), we review research to find the recommended strategies for each metacognitive process identified in this section.

5.3. Instructional strategies for triggering metacognitive processes

5.3.1. Instructional strategies for 'decision-making'

Decision making process is defined as generating possible options for a given situation, and evaluating options based on set of information (Bögeholz, 2006). In decision making process students need to think of many options based on set of information and evaluate them based on domain knowledge expertise (Gresch, 2012). Decision making thus demands for deep reasoning ability among students. Decision making can be triggered using series of deep reasoning questions (Aurisicchio et al., 2007) as well as providing options for selection (Ullman & D'Amboise, 1995). Guidelines suggested for development of question prompts were reflection of expert thinking, address students misconceptions and connection to prior content knowledge.

Addition of self-regulation mechanism to trigger metacognition was worked as catalyst in decision making process (Gresch, 2012). Formative assessment questions can promote self-regulation and feedback will guide learner to expected target performance. Setting up learning goal is essential component for self-regulation. Feedback helps learner to identify gap (Nicol, 2006) between actual performance and expected performance and will guide learner to reduce this gap. Addition of formative assessment in the material can help learner to tune thinking process. Formative assessment question will work as pointers to focus learner attention to major design aspects and formative assessment questions with feedback can promote self-regulations. Decision making process can be triggered using formative assessment in which series of deep reasoning questions were developed at decision step and feedback provided to guide learner for self-monitoring to aid decision process.

5.3.2. Instructional Strategies for 'concept integration'

Concept integration process expects students (Chen et al., 2011) to associate different pieces of information based on domain knowledge. Concept integration also requires knowledge of multiple representations with visual thinking (Ronen and Eliahu, 2000). In concept integration, it is expected to recall appropriate concept, identify inter-relationship between various concepts and connect relevant concepts. Concept integration thus requires recall of appropriate concepts and self-reflection is required. One of the strategies for self-reflection is question prompts with feedback.

Concept integration process shows similarity with knowledge integration process for inquiry learning (Linn et.al. 2003). Opportunity for experimentation was recommended strategy for knowledge integration (Linn & Hsi, 2000). Experimental design suggested in ISLE lab (Etkina et al., 2011) provides opportunity for students to explore real world challenges. Instructional activities should be embedded in inquiry cycle with appropriate scaffolds and reflection. (Etkina et al., 2011). Guided inquiry cycle with experimentation opportunity is a suggested strategy for inquiry learning which promotes knowledge integration. We selected guided experimentation opportunity to stimulate concept integration process in TEEL-EDesC.

5.3.3. Instructional Strategies for 'synthesis'

Synthesis is the mechanism which forces student to think about entire system. Synthesis involves thinking in terms of the system as a whole, and needs decision making, information integration, multiple representations as well as opportunity for experimentation. There is a need to provide an opportunity to converge thinking process by putting all concepts and decisions together. In addition to the recommended strategies for decision making and concept integration that were covered in previous sections, supportive summary statements were recommended to develop structuring of the task (Reiser, 2004) to converge students thinking process. Supportive design statements as design scaffolds which basically are key conceptual decision statements were selected from entire design process and added into modules.

In summary, TELE-EDesC should contain strategies which can trigger required cognitive processes like decision making, concept integration and synthesis. This also needs association of information which need to be processed as chunks. Formative assessment questions and feedback, experimental design with guided approach are two strategies suggested for TELE-EDesC. Metacognition was triggered using deep reasoning formative assessment questions which can develop strategic knowledge in students helping them in decision making process and feedback tune self-learning. Experimentation opportunity provides multiple options and guidance for selected option. Concept integration process requires triggering of appropriate information from knowledge base and its application for decisions. This process can be triggered using question driven approach as well as multiple representations. Table 5.3 shows the instructional strategies identified to trigger metacognitive processes of structure open ended problem competency.

Table 5.3. Instructional strategies for triggering metacognitive processes

Metacognitive Processes	**Theoretical basis**	**Instructional strategies**
Decision Making	Planning, monitoring and evaluation	Formative assessment question
	Self-regulation	Feedback
Concept Integration	Knowledge integration	Experimental design
	Information visualisation	Interpret Multiple Representations
	Reflection	Question prompts with feedback
Synthesis	System Thinking	Summary statements

These instructional strategies identified to trigger metacognitive processes now need to be converted into learning activities within TELE-EDesC. Towards this goal, we reviewed multimedia design principles and interactivity design principles, which informed us in the design of learning activities within a technology enhanced learning environment. We refer to these learning activities in TELE-EDesC as *Learning Dialogs*.

5.4. Design of Learning Dialogs

In TEL environments, instructional scaffolding is recommended to assist learners for achieving higher level of attainment. Instructional scaffolding (Wood, Burner & Ross, 1976) is two-way interaction (Bull et al., 1999) between the learner and the environment in such a way that the learner is actively engaged in the learning activities with reciprocal process (Bull et al., 1999). Reciprocal process means learner interacts with the system and system reciprocates for actions of learners thus learner gets active assistance in learning process (Rogoff, 1990). Examples of instructional scaffolding in TEL systems include electronic note book with embedded functions like glossary, note-taking (Hadwin &Winne, 2001), interactive videos (Zhang et al., 2006) and interactive videos with facility for note-taking, supplemental sources and practice questions (Delen et al., 2014).

We use instructional scaffolding as a base to design the Learning Dialogs in TELE-EDesC, in order to realize the instructional strategies (identified in Table 5.3) within the TEL environment. *Learning Dialogs* are thus the learning activities that learners perform to attain the outcomes related to engineering design competencies. The term 'dialog' indicates the two-way reciprocal process of instructional scaffolding that is implemented in TELE-EDesC. When the learner interacts with TELE-EDesC and performs the activities, the TELE-EDesC system provides customised feedback, structured information and summarised conceptual statements.

Interactivity design principles are applied while designing Learning Dialogs to ensure reciprocal process of instructional scaffolding. Interactivity in visualisation has been known to support guided inquiry and results into higher cognition (Colaso et al., 2002; Jensen et al., 2002; Korhonen & Malmi, 2000; Naps et al., 2003; Tversky et al., 2002). One of the biggest challenges in interactive learning environment is cognitive load, the overloading of memory capacity due to increase in cognitive process needs (Mayer & Moreno, 2003). Interactivity design principles (Mayer 2009, 2005a) such as, guided discovery, pre-training, pacing, feedback, and reflection aim to reduce cognitive load of learner. Guided discovery principle means addition of scaffolding agents in the learning environment. These agents will reduce unnecessary cognitive process further reducing cognitive load. Pre-training principle suggests helping learners connect the new content and skills with their prior content information. Pacing principle demands learner control over the pace of learning material. Feedback on the activities performed by learner should be explanatory.

5.4.1. Learning Dialogs for SOP competency

We designed Learning Dialogs implementing each instructional strategy in Table 5.4, to trigger students' metacognitive processes to attain SOP competency: decision making, concept integration and synthesis.

An important strategy used to trigger students' decision making metacognitive process is formative assessment. Formative assessment questions include deep reasoning questions at decision making step with feedback to guide learners to support decision or provide reasoning. We created Learning Dialogs implementing formative assessment for decision making using guided activity principle and feedback principle, in addition to interactivity design principles described in the previous section. Guided activity principle (Mayer, 2004; de Jong, 2005) states that "students learn better when they interact with a pedagogical agent who guides their cognitive processing rather than when they receive direct instruction without any guidance concerning how to process the presented information or when they engage in pure discovery". Feedback principle states that "students learn better when explanatory feedback is received than only corrective feedback" (Moreno, 2004).

Learning Dialogs that implement formative assessment at decision making steps are referred to as Decision Making Task Questions (DMTQ). DMTQ is a conceptual question in which various choices are given to students to include all plausible decisions related to the question. For each choice, feedback is designed considering seven principles of effective feedback in self-regulation (Nicol, 2006). Feedback is explanatory feedback and not just corrective feedback. Feedback works as prompt in decision making process which guides students to reasoning of wrong answers and pointer to correct answer. Fig. 5.3 shows an example of a DMTQ Learning Dialog.

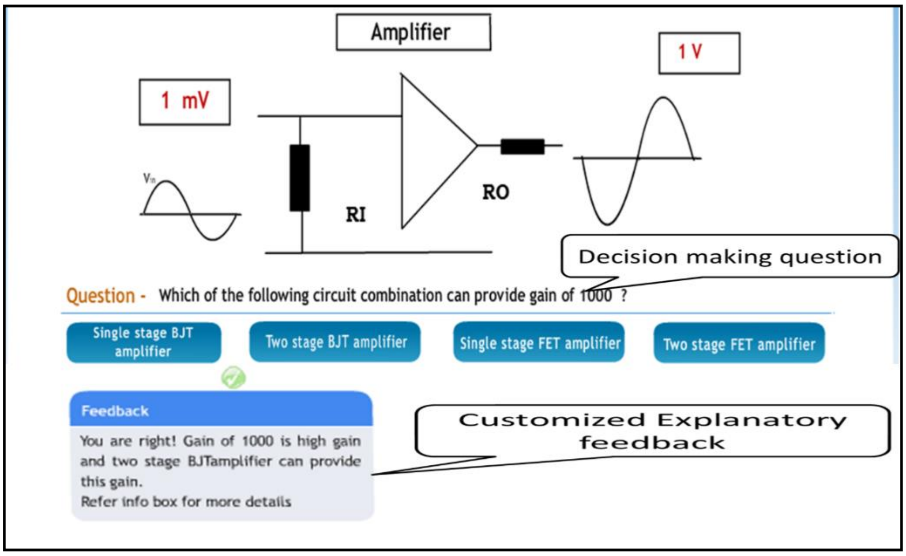


Fig. 5.3. Decision Making Task Question (DMTQ) Learning Dialog

One strategy to trigger concept integration is by using guided experimentation. We designed *Simulative Manipulations* (Chen et al., 2011) as a Learning Dialog in TELE-EDesC to provide experimentation opportunity to students. We created Simulative Manipulation using guided activity principle. In Simulative Manipulation, students are allowed to select different parameters of design and changes are shown as graphs or waveforms. Feedback is provided in the form of text or question prompt. We used feedback principle to design feedback of Simulative Manipulation(SM). SM essentially included simulations of graphs or waveforms based on various input values. Fig. 5.4 shows an example of a simulative manipulation Learning Dialog.

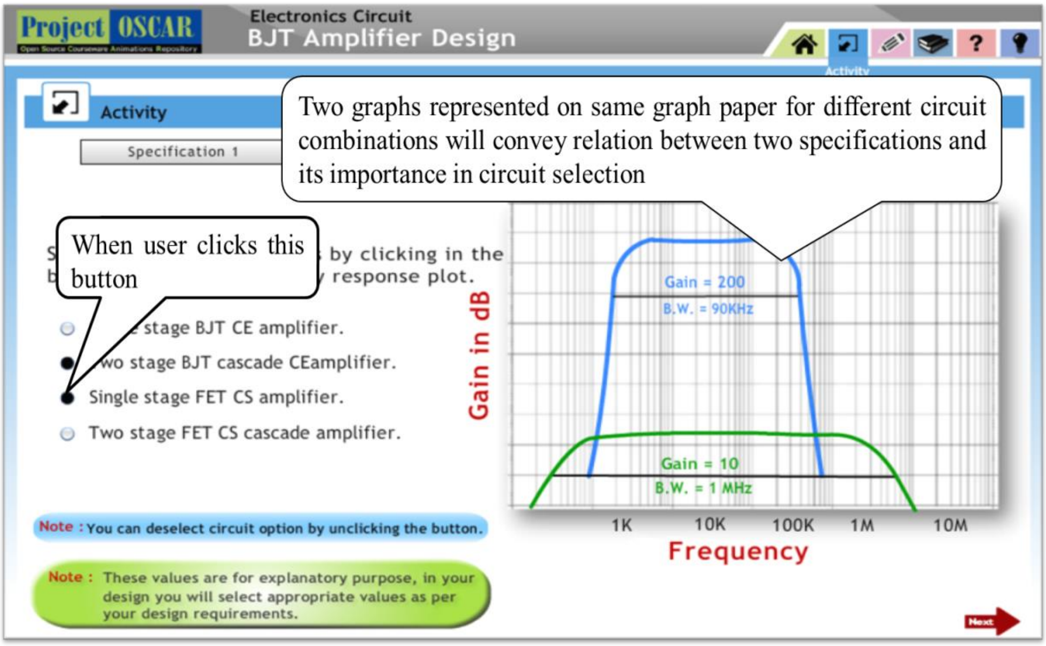


Fig. 5.4. Simulative Manipulation Learning Dialog

Visualisation of graphs and waveforms are abstract concepts in electronics and students face difficulties in understanding and applying these concepts (Ronen & Eliahu, 2000). Hence the concept integration process requires multiple representations with guidance to connect various representations.

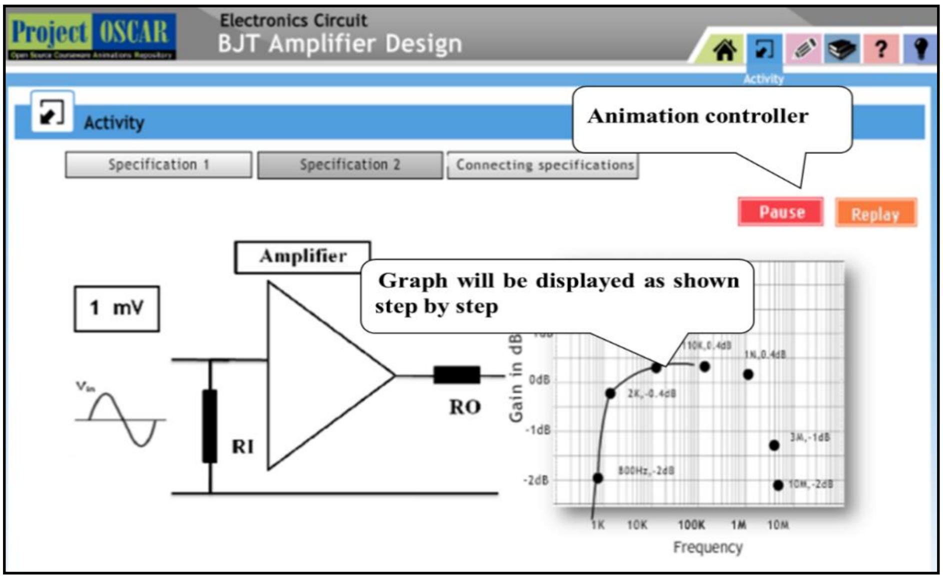


Fig. 5.5. Controlled Animation Learning dialog

We added *Controlled Animations* as a Learning Dialog for this goal, in which the learner can control pace of animation in such a way that connection between different representations can be linked together. We applied pacing principle which states that "Students learn better when allowed to control the pace of presentation of the instructional materials". Self-paced animations are helpful for knowledge integration which will be helpful for concept integration. Fig. 5.5 shows an example of a controlled animation Learning Dialog.

Concept integration is also addressed via formative assessment questions that elicit concepts related to the design problem. We refer to these as *Concept Clarification Questions (CCQ).*We created CCQ using pre-training principle which states that "Students learn better when they receive focused pre-training that provides or activates relevant prior knowledge". CCQs work as question prompts that connect students to domain specific prior knowledge. Multiple choices given to students mainly address either misconceptions or relate to prior knowledge. Feedback content is similar to DMTQ feedback and mainly provides explanation for association of knowledge. Fig. 5.6 shows an example of a CCQ Learning Dialog.

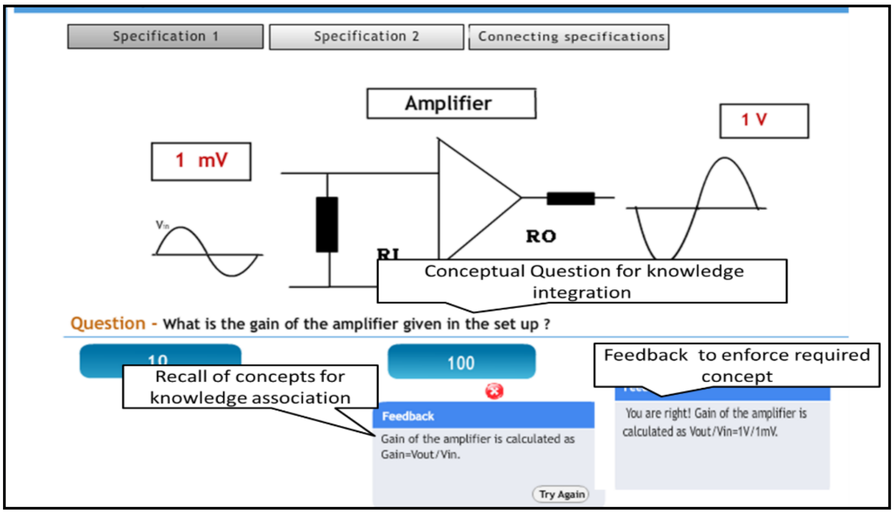


Fig. 5.6. Concept Clarification Question (CCQ) Learning Dialog

Synthesis metacognitive process requires decision making and concept integration as well as application of both simultaneously in an embedded manner. To ensure that students do so, we used feedback principles of instructional design by adding *Information Agents*. These agents provide information and will appear on demand from the learner. We also added design scaffolds in the form of summary statements, referred as *Capsule Recommendations*. After undergoing all activities of TELE-EDesC, if students read these recommendations they will be able to assimilate and synthesis the Structure Open Problem process. Fig. 5.7 shows an example of a Capsule Recommendation Learning Dialog.

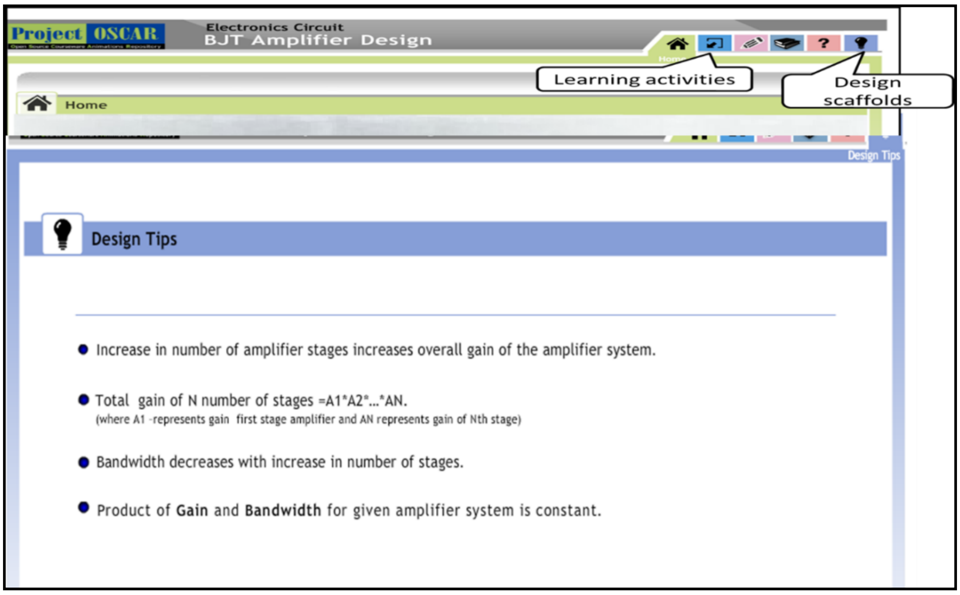


Fig. 5.7. Capsule Recommendation Learning Dialog

Table 5.4 summarizes the process of design of TELE-EDesC. It shows the mapping between metacognitive processes needed to attain SOP design competency (Section 5.2), instructional strategies that trigger these metacognitive processes (Section 5.3), and the use of interactivity design principles to design Learning Dialogs in TELE-EDesC: decision making task questions (DMTQ), concept clarification questions (CCQ), simulative manipulations (SM), controlled animation (CANM), simultaneous multiple representations, information agents and capsule recommendations.

Table 5.4. TELE-EDesC Learning Dialogs for metacognitive processes of SOP

Metacognitive processes	**Theoretical basis**		**Interactivity Design Principles**	**Learning Dialogs of TELE-EDesC**
	Theory	**Instructional strategies**		
Decision Making	Metacognitive strategies	Formative assessment question	Guided activity and feedback	Decision Making Task Question(DMTQ)
	Self-regulation	Feedback		
Concept Integration	Knowledge integration	Experimental design and feedback	Guided activity and feedback	Simulative Manipulation(SM)
	Information visualisation	Interpret Multiple Representations	Pacing Controlling	Self-controlled animation
	Reflection	Question prompts	Pre-training	Concept Clarification Question(CCQ)
Synthesis	System Thinking	Summary statements	Feedback	Capsule Recommendations

5.5. Framework for developing TELE-EDesC

Based on the steps described in Sections 5.2-5.4, we propose a pedagogical framework for the development of a TEL environment for engineering design competencies. Fig. 5.8 shows the steps of pedagogical framework that emerged from section 5.2 to 5.4.

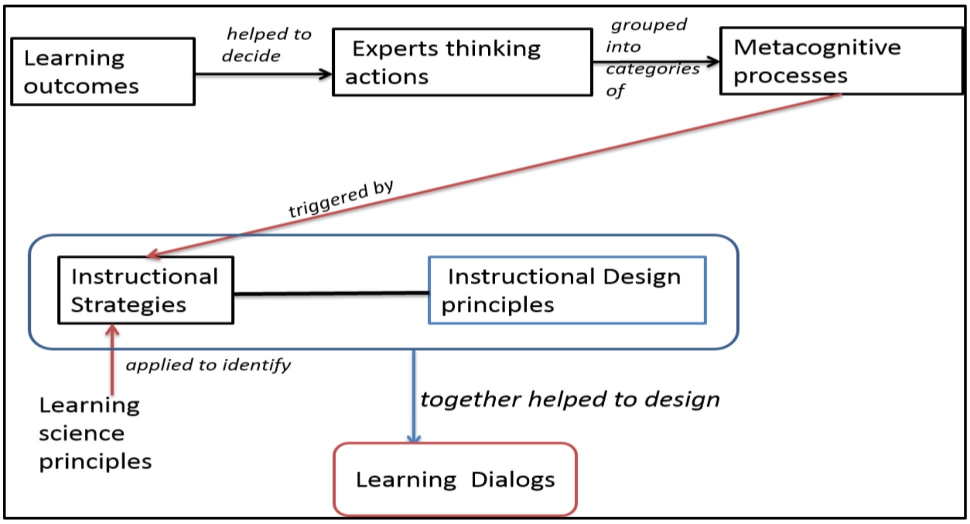


Fig. 5.8. Pedagogical framework to design TEL environment for engineering design competencies

The major goal of TELE-EDesC Learning Dialogs is to provide support to learners to attain learning outcomes of desired competency (SOP as example). Learning outcomes are defined through sub-competencies and expected target behaviour (Chapter 4). In order to decide which type of Learning Dialogs to be incorporated in TELE-EDesC, we first analysed experts' actions for attainment of learning outcomes related to SOP competency. Qualitative content analysis of experts' solution to design problems was carried out which indicated that certain metacognitive processes were being used frequently in the design solution; for example, to attain SOP competency, the metacognitive processes were decision making, concept integration and synthesis. We then analysed literature to identify the instructional strategies to trigger these metacognitive processes. Further, Learning Dialogs are designed using instructional design principles for developing interactive learning environment from the identified strategies. This process provides the broad steps of the pedagogical framework for designing a TEL environment and answered the research question: 'RQ 2: How to develop TEL environment to teach engineering design competencies?'

Table 5.5 shows application of pedagogical framework to develop TELE-EDesC for "Structure Open Problem (SOP) design competency.

Table 5.5. Pedagogical framework to develop TELE-EDesC for “Structure Open Problem (SOP) competency

Learning outcomes	**Experts design actions (codes of design solution)**	**Metacognitive processes**	**Theoretical Basis**		**Interactivity Design principles (to operationalize strategy in TEL environments)**	**Learning Dialogs with metacognitive triggers**
			Learning science principles	**Instructional Strategies**		
1. Identify all the relevant visible and hidden specifications in detail.	Apply concepts/principles to identify specifications.	Concept Integration	Knowledge Integration (Reflection)	Question Prompts	Pre-training and feedback	Concept Clarification Question (CCQ)
	Decide appropriate specification.	Decision Making	Metacognition (Planning of learning)	Formative assessment Questions	Guided activity and feedback	Decision Making Task Question (DMTQ)
2. Interpret specifications.	Interpret specification using known concepts	Concept integration	Knowledge Integration (Information Visualisation)	Interpret Multiple representation	Pacing	Self-controlled animation
1. Apply all the relevant specifications to take decisions to structure problem.	1. Apply specifications to take decisions.	Decision making	Metacognition	Formative assessment Questions	Guided activity and feedback	Decision Making Task Question (DMTQ)
2. Decide all interconnections of the system based on given and identified specifications.	2. Identifying connection between specifications to decide structures of problem	Concept integration and decision making	Knowledge Integration and metacognition	Experimental design	Guided activity and feedback	Simulative Manipulation
	3.Apply integrated set of specifications to take decisions	Decision making	Metacognition	Formative assessment Questions	Guided activity and feedback	Decision Making Task Question (DMTQ)
1. All the decision steps identified.	1. Link decision steps to each other	Concept integration synthesis	Knowledge Integration and Metacognition	Decide sequence of concepts.	Guided activity and feedback	CCQ
2. All steps sequenced correctly based on specifications.	2.Decide sequence of decision steps	Decision making	Metacognition	Decide formative assessment sequence	Guided activity and feedback	DMTQ
1.Write problem statement by systematically integrating specifications, decision steps, devices, structures etc.	Synthesis of all above tasks which involves recalling of concepts, deciding the structures, applying information and integrating process. Overall system thinking is done by students.	Synthesis	System thinking	Write summary statements	Feedback	Information Agents Capsule Recommendations

5.5.1 Guidelines for creating TELE-EDesC Learning Dialogs for SOP

While the framework described in Table 5.5 is useful for the purpose of developing TEL environment for engineering design competencies, a researcher, curriculum designer or instructor wishing to develop TELE-EDesC modules in a particular topic needs specific guidelines to undertake the following steps:

1. Content preparation:

Topic is selected from the course. Topic should be relevant to the purpose of TELE-EDesC modules. After selection of topic users should be able to select appropriate design problem. Since we have selected 'Innovative' design problems for TELE-EDesC, the relevant design problem need to be selected. Problem should be analysed in detail to find the learning objectives. Specific measurable performance based on sub-competencies need to be identified. In each design problem solving various key concepts are involved. Each of the key concepts should be treated separately.

2. Create Learning Dialogs:

Learning Dialogs for SOP competence are already decided using framework table (table 5.5). Table also provides type of Learning Dialogs aligned with Learning Objectives. For each of the Dialog, content should be selected correctly and Dialog need to be written accurately. For e.g. Writing Questions of DMTQ, decision steps should be appropriately identified and Question should be formed. In animation and Simulative Manipulation(SM) appropriate part of the content should be selected. In SM part of problem solution need to be selected where two variables interact with each other. Type of Multiple Representations also should be identified. Key design concepts need to be identified. Since each of the activity contains explanatory feedback, correct directional feedback need to be written.

Guidelines are needed to implement these steps in order to come up with an instructional design document for a TELE-EDesC module. We have created a template encoding and illustrating these guidelines in a detailed manner for the SOP competency. The user of this template could be a researcher, curriculum designer or instructor wishing to design TELE-EDesC module in a specific topic. This template is in the form of slides, where guidelines and instructions are present on one slide, and a blank slide is provided following each guideline for the user to fill. Sample slides are shown in Fig. 5.9 and 5.10 below which illustrates the guidelines for creating learning dialog for different learning outcomes and writing feedback for learner.

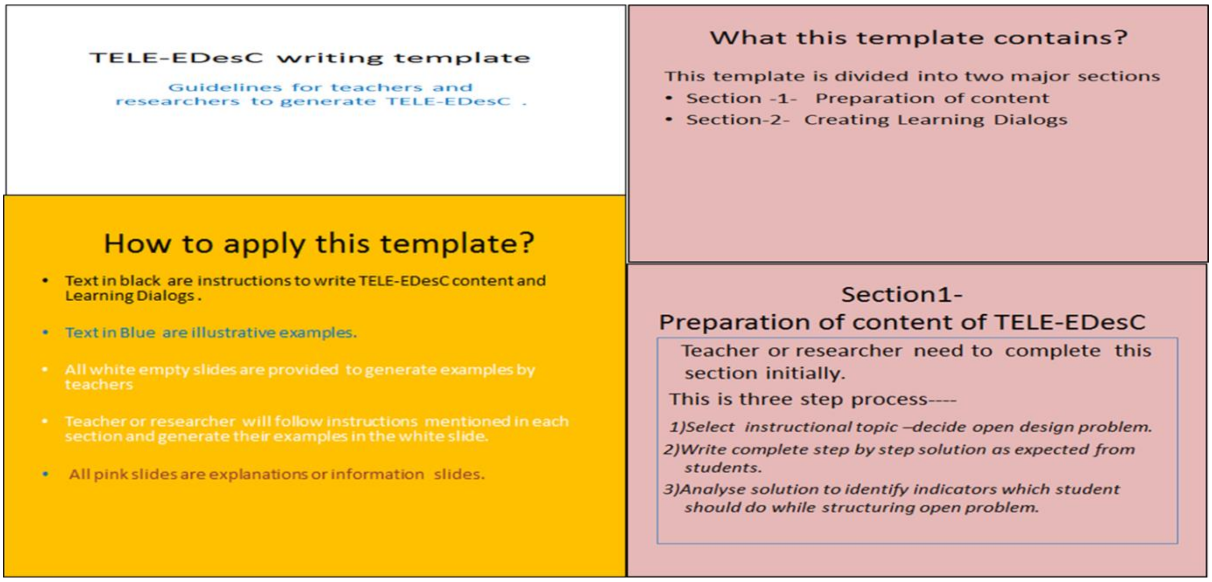


Fig. 5.9. Slides in the template

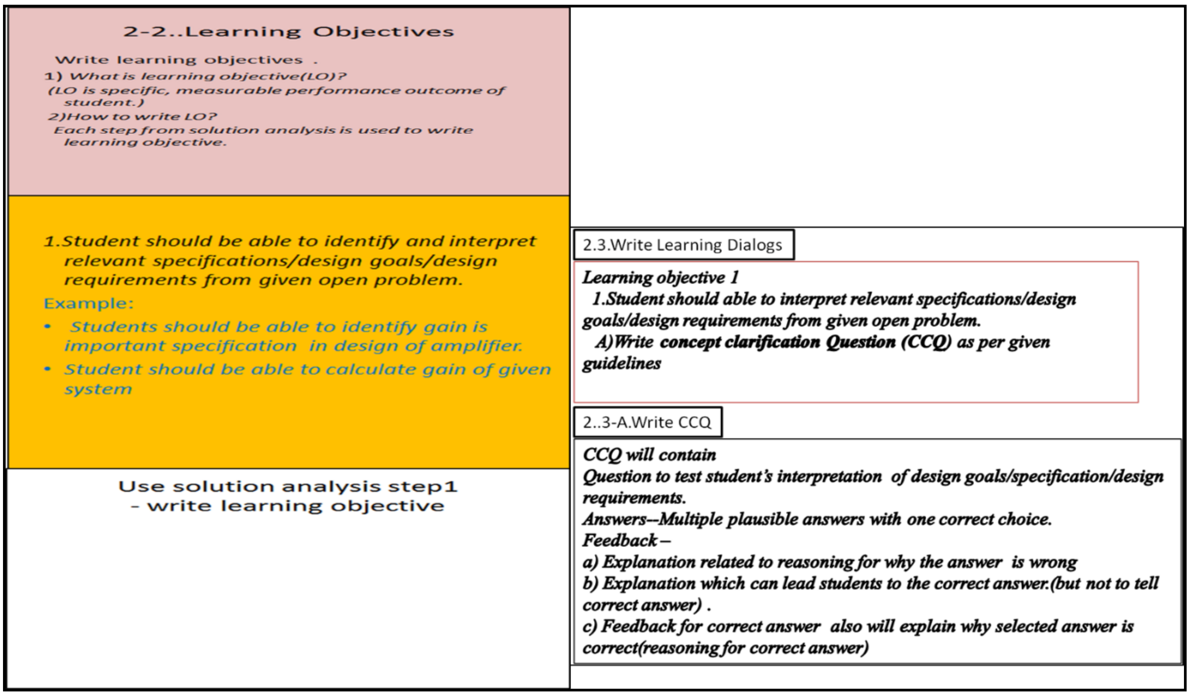


Fig. 5.10. Template slides showing guidelines for Learning Objectives and Learning Dialogs

The next section (5.6) shows a detailed step-by-step description illustrating the application of these guidelines for TELE-EDesC modules for SOP competency in the topic of amplifier design.

5.6. Example of development of TELE-EDesC modules

The template to develop TELE-EDesC modules is divided into two parts. The first part of the template guides the user for selecting content for the modules. This phase is referred as "Content preparation phase". The second part of template contains guidelines to create corresponding Learning Dialogs

5.6.1. Content preparation phase

Content preparation includes selection of instructional topic, selection of open design problem, writing complete solution, analysis of solution and decision of small modules in the entire solution. Table 5.6 shows the guidelines and examples for the steps mentioned in the flow diagram (Fig. 5.11).

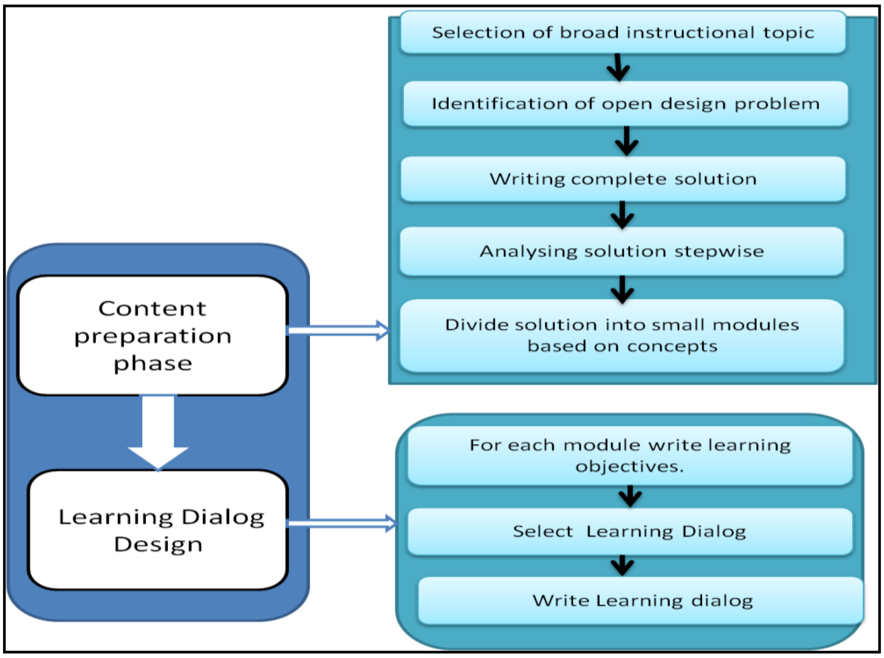


Fig. 5.11. Flow diagram of Template

Table 5.6. Guidelines for content preparation

Steps	**Guidelines**	**Example**
Instructional topic is selected which includes design problems.	Choose instructional topic from the chapter of book or module from the course for which design is a relevant goal.	Instructional topic selected is amplifier design using BJT, FET from Electronics Circuit course.
Open design problem is selected from chosen instructional topic	Choose design problem, which has features of open design problem: All design requirements or goals are not explicitly mentioned in the problem statement and designer needs to extract relevant information from problem and decide design goals. Open design problem has multiple solutions.	A muscle signal of amplitude 1mV and frequency range of 100Hz to 1MHz need to be recorded for further analysis. Recorder need 1V input so that it can record applied signal. Suggest circuit to meet above requirements.
Complete solution is written for the selected problem.	Solution should contain all steps and reasoning for each decision step. In this step it is expected that instructor should write all steps with proper reasoning.	Explanation: Some of the requirements like 1mV signal input, frequency range and 1V output is given in problem but which circuit needs to be designed and need to consider loading effect is not mentioned in the problem. Circuit for the given problem can be designed either using BJT or FET or combination.
Extract and annotate the information relevant to SOP competency	The information pieces should be identified from problem solution based on following guidelines.	In the open problem gain, bandwidth, impedance are specifications /design goals/requirements.
	1) Identify what are goals /specifications/ design requirement of problem from solution.	
	2) Identify and list key decision steps from problem solution.	For given gain how many stages are required? Which device needs to be used to attain given impedance etc.
	Identify sequence of decision steps.	1. Identification of gain as high gain. 2. Selection of circuit to satisfy high gain
	Write structured statement.	Design single/multistage BJT/FET amplifier for specifications
Small modules are decided from entire solution.	Important concepts required to write solution should be identified and each module ~~is~~ should be designed based on single concept.	Concept identified in amplifier design is relation between gain and bandwidth. Module1—Show link between gain and bandwidth to decide amplifier circuit

5.6.2. Design of Learning Dialogs for SOP Competency

As shown in flow diagram (Fig. 5.6) the first step is to write leaning objectives for given module.

a) Learning objectives based on expected learning outcomes

Learning objectives are written using content and learning outcomes of main competency, that is, SOP. Expected learning outcomes mentioned in Table 5.1 decide the specific measurable outcomes of the design competency. The content is selected based on the problem solution.

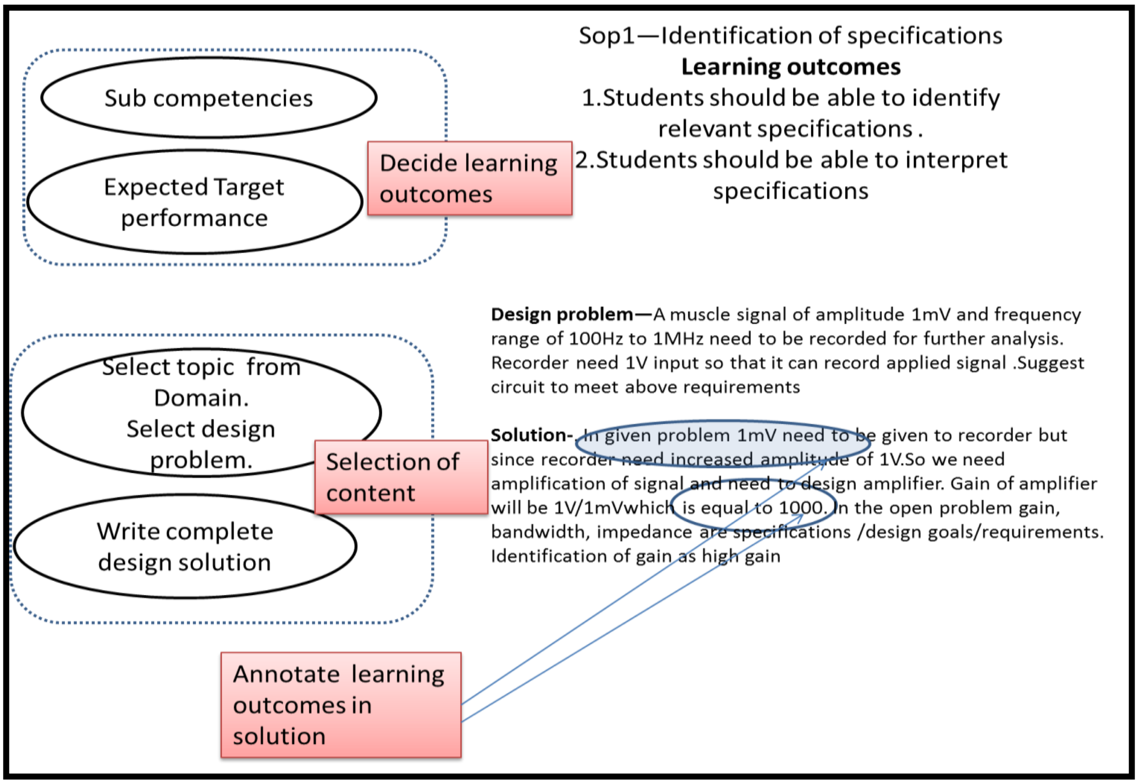


Fig. 5.12. Process to write learning objectives

Learning outcomes are annotated (Fig. 5.12) in the solution and then learning objectives are written. Example of learning objectives for the topic of amplifier design is as shown in Fig. 5.13.

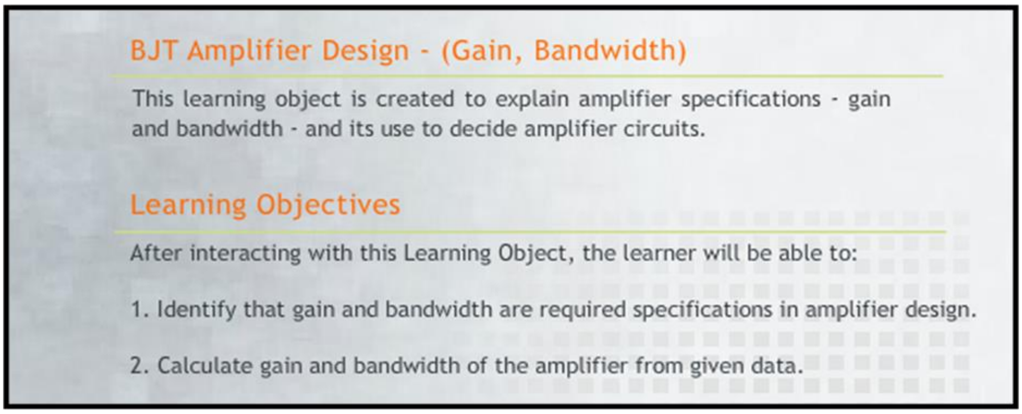


Fig. 5.13. Example of learning objectives for topic of Amplifier Design

For each of the learning outcomes of sub-competency, we wrote learning objectives based on content (Fig. 5.7).

b) Learning Dialogs of TELE-EDesC for amplifier design

Learning Dialogs are aligned with the learning objectives. Since learning objectives are based on learning outcomes, table 5.5 is provides Learning Dialogs to achieve desired learning outcomes (last column of table 5.5). In next paragraphs, sub-competency wise learning objectives and Learning Dialogs are described along with screenshot of TELE-EDesC module.

Learning Dialogs for SOP1:-.

Learning Dialogs to attain the target performance of sub-competency SOP1, that is, ‘identification of specifications’ are Decision-making task question (DMTQ), Concept clarification question (CCQ) and controlled animations. Fig. 5.14. shows this in the context of amplifier design.

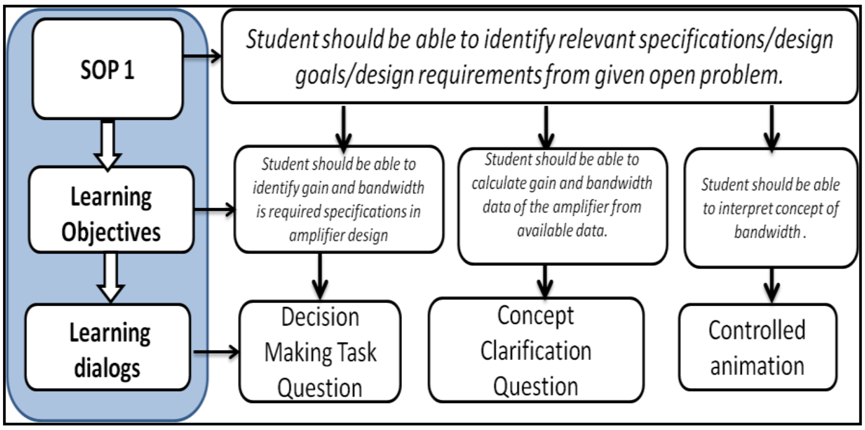


Fig. 5.14. Learning Dialogs for SOP1 (ref: table 5.5)

Guidelines to write DMTQ for SOP1:

DMTQ will contain

Question to identify which is relevant specification from given set of specifications.

Answers--Multiple plausible answers with one correct choice.

Feedback –

a) Explanation related to reasoning for why the answer is wrong

b) Explanation which can lead students to the correct answer (But not to tell correct answer)

c) Feedback for correct answer also will explain why selected answer is correct (reasoning for correct answer).

Example of DMTQ Learning Dialog for topic of amplifier design is developed using above guidelines and shown in Fig. 5.15

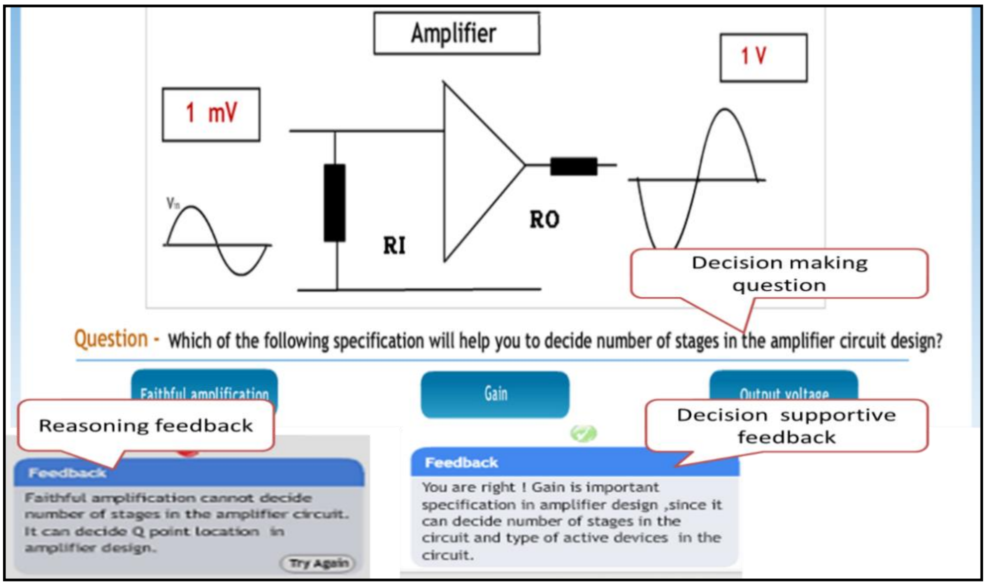


Fig. 5.15. DMTQ for learning outcome of SOP1

Guidelines to write CCQ Learning Dialog: CCQ will contain

Question should test student's interpretation of design goals/specification/design requirements.

Answers--Multiple plausible answers with one correct choice.

Feedback –

a) Explanation related to reasoning for why the answer is wrong.

b) Explanation which can lead students to the correct answer (but not to tell correct answer).

c) Feedback for correct answer also will explain why selected answer is correct (reasoning for correct answer)

Example of CCQ Learning Dialog for topic of amplifier design is developed using above guidelines and shown in Fig. 5.16.

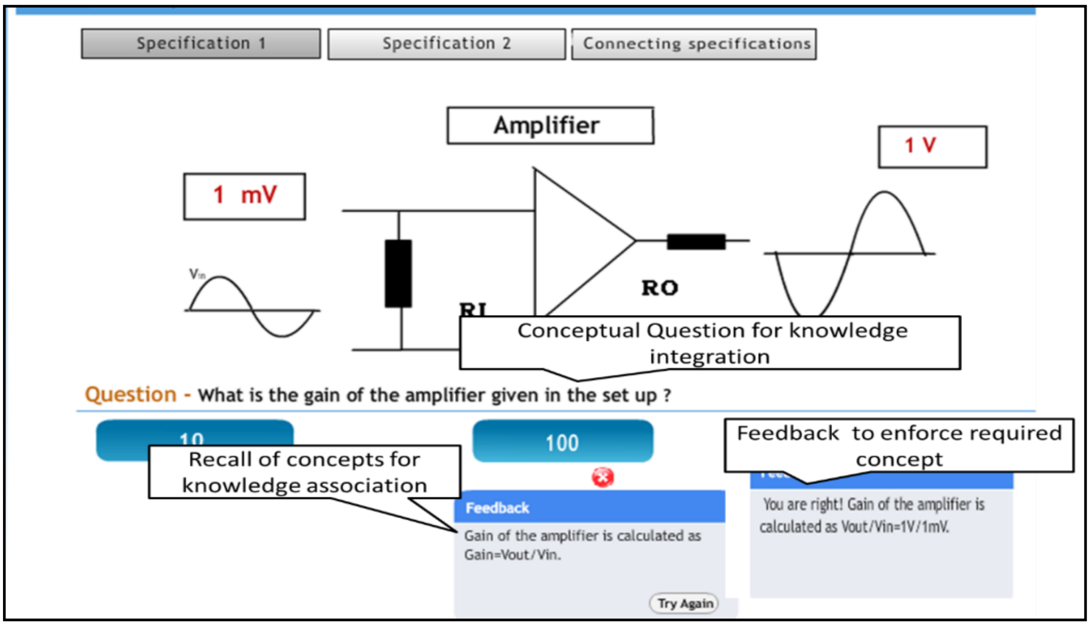


Fig. 5.16. CCQ for learning outcome of SOP1

Guidelines to write controlled animation Learning Dialog:

- Select specification which may need either graph/waveform/circuit /blocks/process (representations) for explanation.
- Identify appropriate graph/circuits/waveform/block /process to represent specification.
- Identify parameters to be represented in graph/circuit/block /process.
- Describe relation between selected parameters either using tables or separate slides.
- Animation will contain frame by frame variations.
- In each frame show representations simultaneously.
- Provide start, stop and pause buttons.

- Animation will explain the specification /design goal/design requirements.

Example of Controlled Animation Learning Dialog for topic of amplifier design is developed using above guidelines and shown in Fig. 5.17.

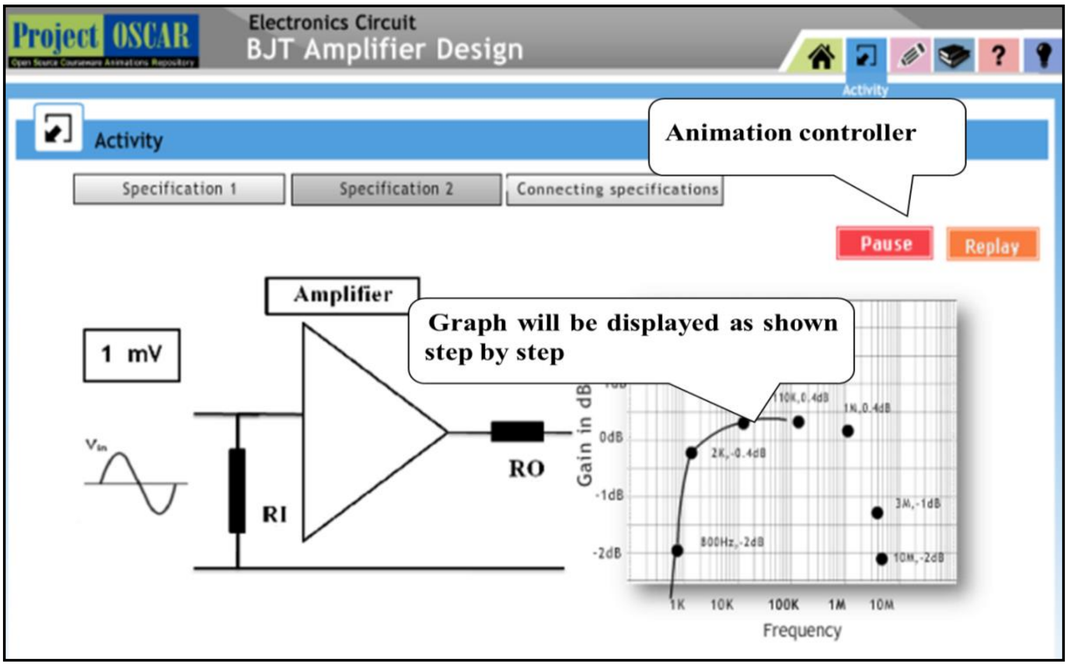


Fig. 5.17. Controlled animation for SOP1

Fig. 5.11 shows an example of an animation for bandwidth specification. To explain the concept of bandwidth we need to plot graph of frequency vs. gain and then show calculation of bandwidth.

Learning Dialogs for SOP2:-

Learning Dialogs to attain sub-competency SOP2 'use specifications to structure problem' are DMTQ and simulative manipulations. These are explained for the amplifier design example in Fig. 5.18.

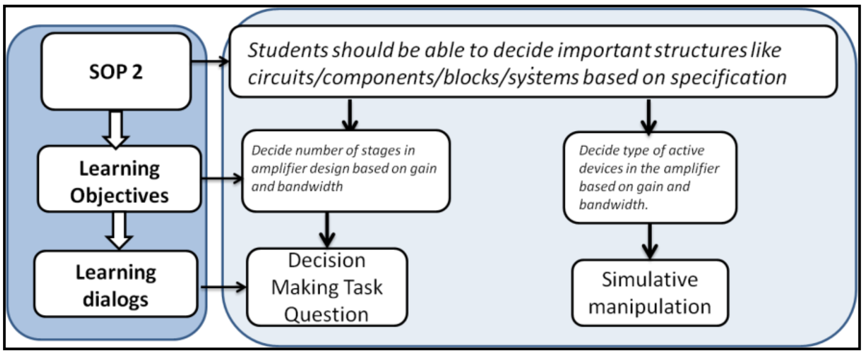


Fig. 5.18. Learning Dialogs for SOP2 (ref table 5.5)

Guidelines to write DMTQ for SOP2: DMTQ will contain

- Question to decide important circuit/ block /system/components for given specifications. Question will include multiple representations.
- Answers will be multiple plausible, mainly targeting misconceptions of students.

Feedback will contain

- Explanation related to reasoning for why the answer is wrong
- Explanation which can lead students to the correct answer (but not to tell correct answer).
- Feedback for correct answer also will explain why selected answer is correct (reasoning for correct answer) and leading students to next decision step

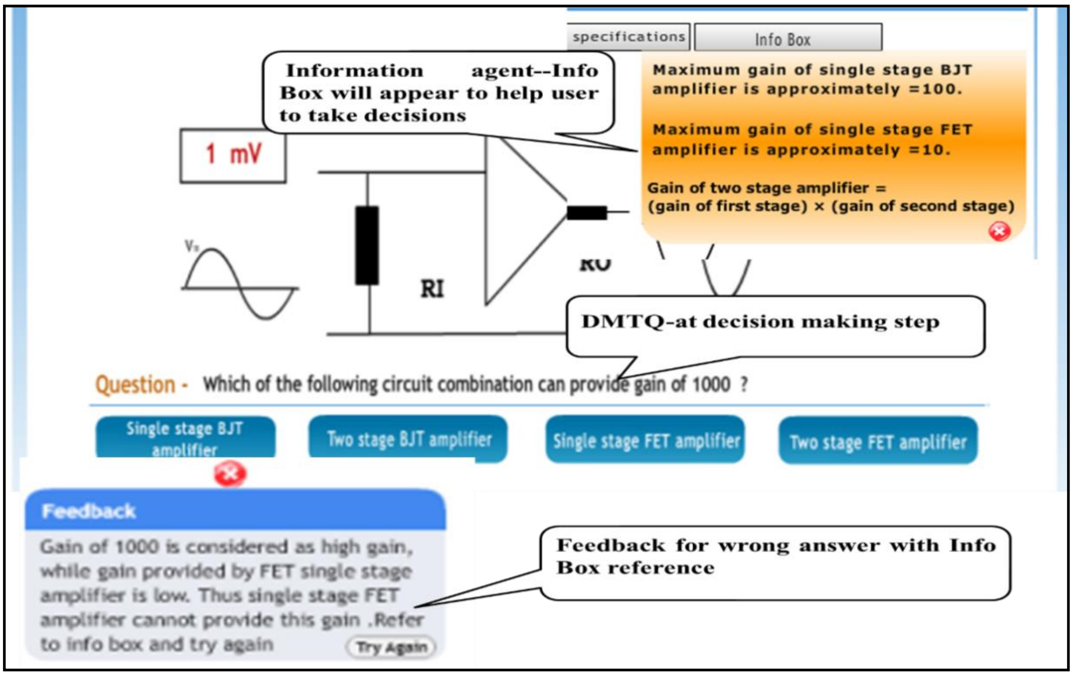


Fig. 5.19. DMTQ and information agents with example

The learning dialog will help learner for decision making as well as information association. This dialog follows guided activity principle through question answer feedback and information agents (Fig. 5.19).

Guidelines to write Simulative Manipulation(SM) for SOP2: SM will contain

- Identification of solution part—what is the content?
- SM can be written for all of the following---
- Part of solution analysis in which different ideas need to be explored.

- Part of the solution in which students need to connect different specifications /design requirements/design goals to each other and then take decisions in design process. Thus SM will be designed based on concepts required to take key decisions in design process.
- How to add simulative manipulations?
- Include variable manipulations such that students should be able to change input variables or parameters or conditions within system and can immediately observe corresponding changes in the output.
- Show Different representations simultaneously
- Add buttons to move forward, backward, increment, and decrement.
- Show Separate frame for each variation.
- TELE-EDesC writer need to select range depending on design requirements

Feedback box to explain the effect of variations or follow up question answer feedback to test student's understanding from animation/variable manipulation etc. should be added.

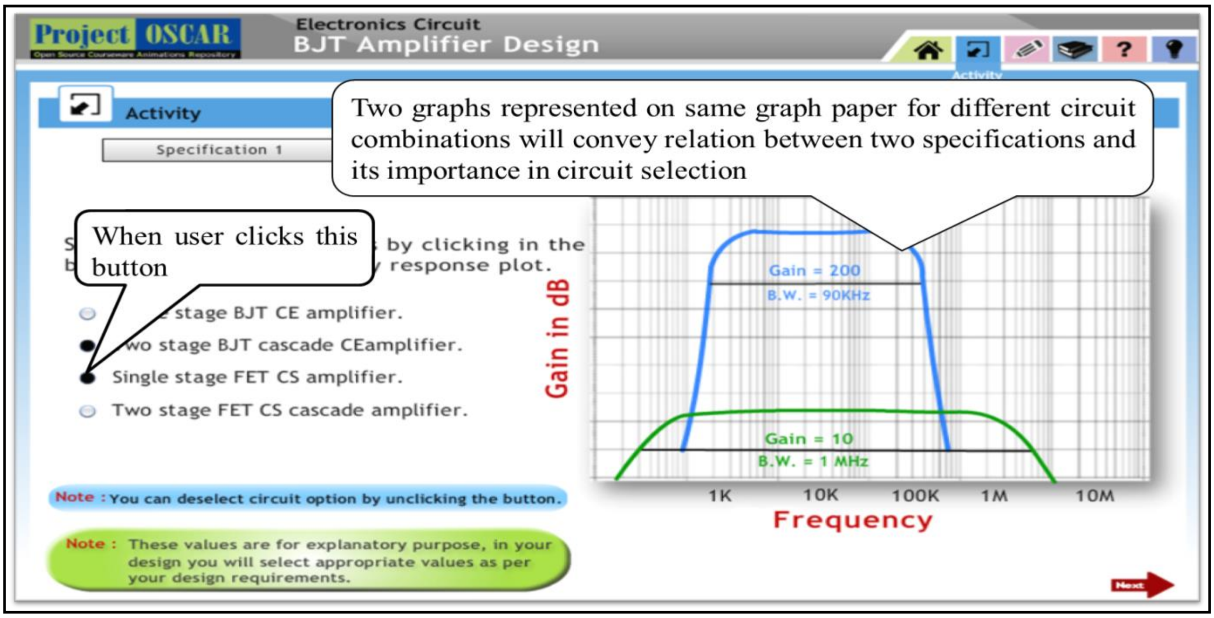


Fig. 5.20. Simulative Manipulation for SOP2

The Simulative Manipulation includes connecting different representations and based on multiple representations learner will be guided for decision making. This learning dialog contains simulations which allow variable manipulations followed by decision making question. Feedback guides the learner to repeat Simulative Manipulation activity. For example, frequency response of different circuits is selected which need different circuits for different frequency responses and also convey concept of gain bandwidth product (Fig. 5.20).

Learning Dialogs for SOP3:-

Learning Dialogs for SOP1 and SOP 2 trigger the metacognitive processes like decision making and concept integration which are required for attainment of SOP3 'sequence decision steps to structure open problem'. The guidelines provided for DMTQ and CCQ in previous paragraphs are applicable to DMTQ and CCQ Learning Dialogs for SOP3 development. DMTQ is designed based on the expected sequence of problem solution.

Learning Dialogs for SOP4

Learning dialog to attain SOP4, 'write structured design statement' includes "Capsule Recommendation" are summary statements to act as design scaffolds. Capsule Recommendations are important summary design concepts students should able to recall when they structure open problems (Fig. 5.15).

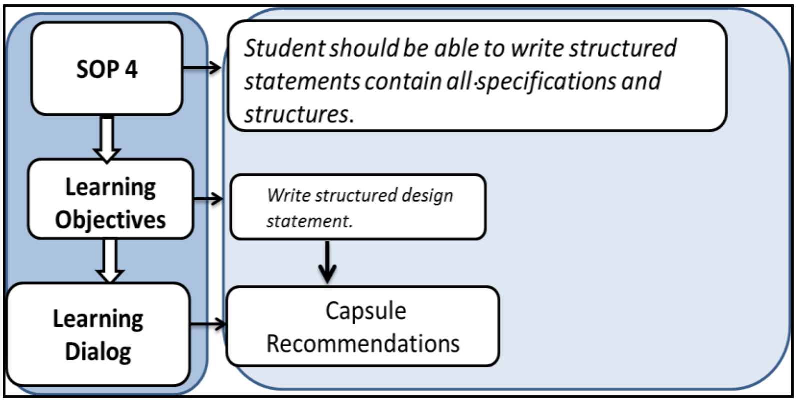


Fig. 5.21. Learning Dialog for SOP4

Guidelines to write Capsule Recommendations are

- Identify important keywords required to support decisions and order.
- Write important keywords which support decisions.
- Decide number of statements based on number of key decisions.
- Write the conceptual statements highlighting design keywords at each key decision step.

Fig. 5.22 shows example of "Capsule Recommendations" for Amplifier design topic.

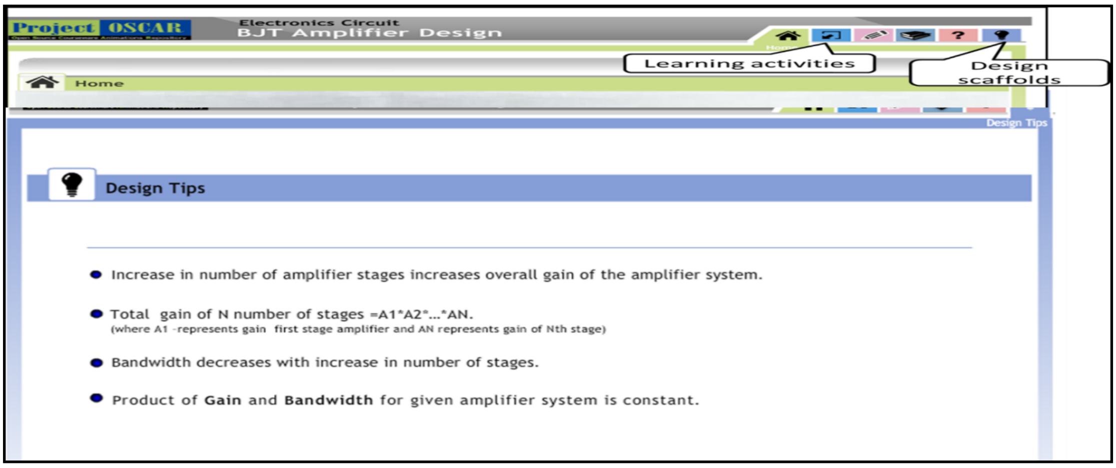


Fig. 5.22. Capsule recommendations (CR) for SOP4

5.6.3. TELE-EDesC modules in analog electronics domain

We applied the template illustrated in Fig. 5.9 and 5.10 described in Section 5.6 to design eight TELE-EDesC modules for SOP in different topics from analog electronics domain (Table 5.7). Screenshots of learning materials are given in Appendix II, and the actual TELE-EDesC modules can be accessed at www.et.iitb.ac.in/~madhuri/<resources>/

Table 5.7. Topics for TELE-EDesC modules from analog circuit domain

Topic	Open Design Problem	TELE-EDesC learning modules developed
DC circuit design	Design of amplifier for given application.	1,Importance of Q point in amplifier design
		2.Location of Q point in amplifier design
		3. Amplifier design based on gain and bandwidth.
Ac circuit design		4. Amplifier design based on impedance.
Power amplifier	Design of audio power amplifier	5. Power amplifier design-impedance matching.
		6. Power amplifier design based on power rating
OP-AMP	Design battery charge indicator	7. Identification of comparator circuit for charge indicator
OP-AMP	.	8. Design of LED indicator and OP-AMP comparator circuit.

Analog electronics was chosen as the main topic for this thesis since it is a foundation course taught at second year level. In addition, analog electronics circuits and its design find application in almost all streams of engineering. The main course objectives are that i) students should be able to identify basic principles of electronic circuits and ii) they should be able to apply principles while solving real world problems. The entire course is spanned over two semesters. The topics from the course which contain design problems were identified to develop TELE-EDesC modules for Structure Open Problem competency. These topics were selected depending on their importance in electronics system design and such that they cover a variety of applications in analog electronics circuits. In addition, the topics were chosen such that they commonly appear in the syllabus of this course as taught in Mumbai University. It can be assumed that these topics are commonly taught in most universities.

The major broad topic for developing TELE-EDesC modules was chosen to be amplifier design. The topic of amplifier design covers a major range of applications in electronics circuit design. If students study these modules then they will be able to design amplifier circuits for audio frequency and radio frequency, and they can design small signals as well as large signal amplifiers. The first two topics – i) DC circuit design and ii) AC circuit design - Amplifier design based on gain, bandwidth and impedance - consider linear region of operation. They use BJT and FET as active devices. In order to further extend TELE-EDesC development, the next topic considers OPAMP as active device with nonlinear region of operation. Thus, topics for development of TELE-EDesC modules were chosen to cover a large range of concepts in analog electronics circuits: in terms of designing for small versus large signals, different frequency range, region of operation, types of active devices, and different conceptual basis. If students study these modules they will able to structure a variety of innovative application problems in analog electronics domain.

In addition to testing the applicability of the template to develop TELE-EDesC modules in various topics, we also tested the usability of the template. The template has been applied by 2 instructors (other than the thesis author) to develop modules in the topics of antenna design and computer programming. It was found that teachers prepared the content appropriately i.e topic of design and open design problem was correctly identified. Learning objectives were also written correctly with specific measurable outcomes and action verbs. Teacher who designed module for topic of antenna design wrote DMTQ, CCQ and SM correctly, but not able to identify proper content for Controlled Animation. Teacher of computer programming identified appropriate content for all Learning Dialogs, but customised feedback for two DMTQ was just explanation and no reasoning was involved.

5.7. Summary

This chapter explained the steps in the development of TELE-EDesC modules. The major contributions of the chapter towards this thesis are pedagogical framework to design TEL environment for engineering design competencies and TELE-EDesC learning modules. The minor contribution is the template to develop learning modules for develop SOP competency.

The pedagogical framework emerged in the chapter answered the research question ‘How to develop TEL environment to teach engineering design competencies?’ The framework guides a researcher, curriculum designer, or instructor to design Learning Dialogs for learning outcomes of engineering design competency. Learning Dialogs include activities for the learner to attain engineering design competencies and the corresponding reciprocative feedback given by the TELE-EDesC system. In this chapter, we identified the Learning Dialogs that target learners’ attainment of Structure Open Problem (SOP) competency.

In addition to the broad pedagogical framework for design of TELE-EDesC, we developed a template that contains detailed steps to choose topics, write learning objectives and create specific Learning Dialogs for SOP competency. We applied the template to create Learning Dialogs for SOP in various topics from analog electronics. We developed eight TELE-EDesC modules for three topics from analog electronics.

This chapter described the last step of the Design Prototype phase of Education Design Research, the overall research method used in this thesis (Chapter 3). The following two chapters, 6 and 7, describe the evaluation and refinement phases respectively, with results of effectiveness testing.

Chapter 6

Evaluation of TELE-EDesC

Chapter 5 described the process of developing the framework for designing a TEL environment for engineering design competencies. Based on the pedagogical framework, Learning Dialogs with metacognitive triggers in TELE-EDesC environment for structure open problem (SOP) competency were designed. TELE-EDesC modules for the topic of amplifier design in analog electronics course were created. In this chapter we describe the testing process of TELE-EDesC modules for SOP in the topic of amplifier design to determine its learning effectiveness. Section 6.1 describes the research method applied for evaluation of TELE-EDesC learning effectiveness. This is the third phase of Education Design Research Methodology (EDR). The analysis of data, results and interpretation are presented from Sections 6.1.-6.4 respectively.

Evaluation of TELE-EDesC learning effectiveness is carried out using a two-step sequential explanatory mixed method design. The research question addressed in this step is RQ 3: "What is the effectiveness of the TELE-EDesC to develop engineering design competencies?" This research design is summarized in fig 6.1 using four steps (Creswell et.al, 2003):

Step 1: Quantitative method that includes collecting and analysing data using statistical methods.

1) Step 2: Intermediate step that involves identifying quantitative data that demands additional explanation, and use of this data to guide development of qualitative method. In this step, qualitative research questions are refined, purposeful sampling process is decided.
2) Step 3: Qualitative method that involves collecting and analysing qualitative data. This step is implemented to explain the results from the quantitative method (Step 1).
3) Step 4: Interpretation of results which indicates the extent to which qualitative data is used to explain quantitative results.

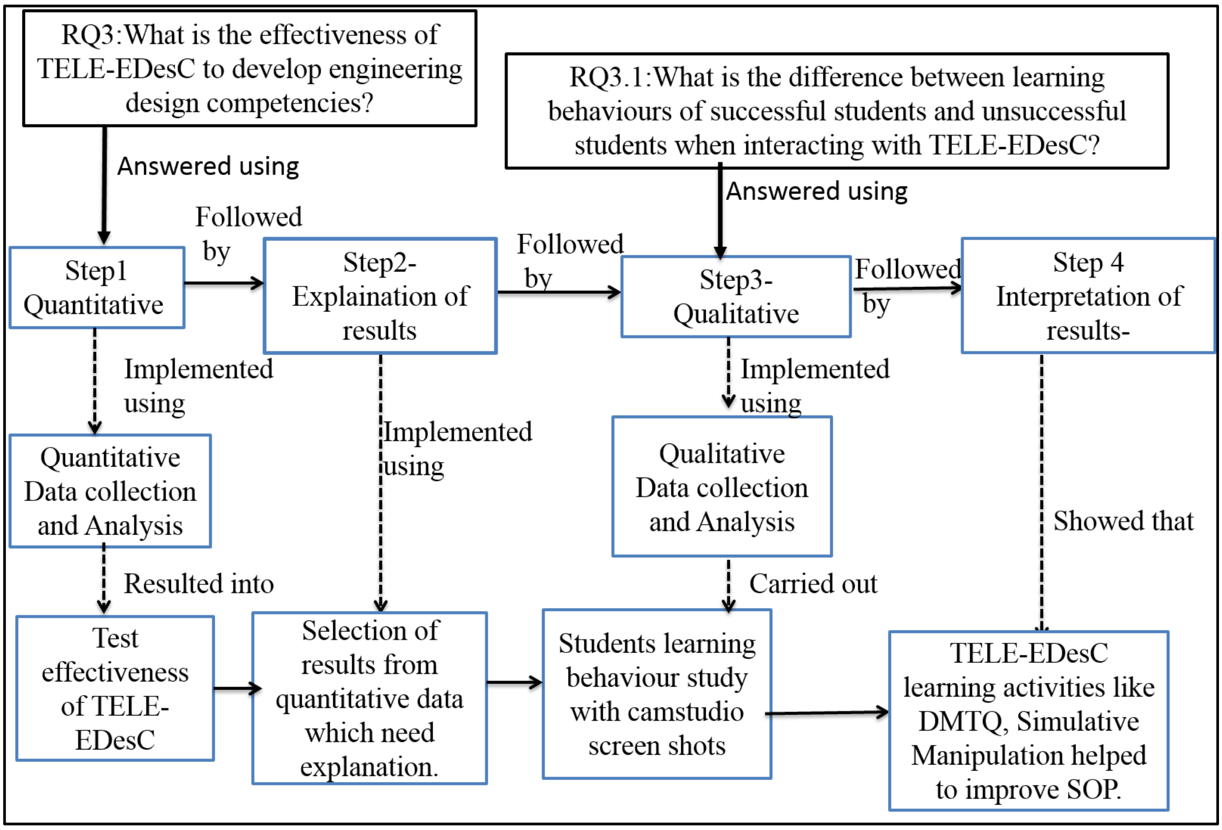


Fig. 6.1. Steps of sequential explanatory mixed method research design

6.1. Quantitative method research design

The research question answered in this step is RQ 3: "What is the effectiveness of TELE-EDesC to develop engineering design competencies?" This question was answered by conducting two-group post-test controlled experiments. The independent variable was the type of learning environment - TELE-EDesC versus explanatory visualisation. The dependent variable was students' development of SOP competency and associated sub-competencies which are identified in Chapter 4.

6.1.1. Participants

The participants of this study were second year engineering students from electronics and telecommunication branch, studying from various colleges in and around Mumbai, India. These colleges were located in urban and semi urban areas. Students were admitted to different colleges based on their marks on an entrance test. The colleges considered for this study covered a range of students from low to high marks on the entrance test. Representativeness of the sample was ensured by selecting colleges with different entry levels as well as locations.

The total number of participants in the study were N=295. All students had familiarity with the content in the visualization, as they had learnt it in the theory course on the same topic in the previous semester. Students were familiar with use of ICT tools for learning as their curriculum includes simulation tools and programming languages at first year level. Students did not have prior exposure to self-learning.

Students from the second year of a four year undergraduate engineering program were selected for this study, since developing engineering design thinking skill along with the content and domain courses starts at second year level. Courses taught at second year level are foundation courses. In these courses, including the analog electronics course which is the focus of this study, students solve design problems of the ‘routine’ level (Brown & Chandrasekaran, 1989) level. They are not trained and exposed to ‘innovative’ level design problems.

6.1.2. Materials and procedure

The TELE-EDesC modules in this study were from three topics in analog electronics – DC circuit design (Q-point), Amplifier AC circuit and OP-AMP comparator. Two sets of instructional materials were developed for each topic, one for the experimental group and the other for the control group. The materials for each group were digital in nature. The materials for each group were intended for student self-learning, that is, without any instruction from a teacher. The experimental group received the materials in the form of TELE-EDesC modules, as described in Chapter 5. The control group received similar content but in the format of *informative visualizations.* Fig.6.2 shows the similarity and differences between the TELE-EDesC and informative visualisations. In both learning materials we added learning objectives as learning goals, both the learning materials contain same circuit diagrams and graphs. The difference was only in the format i.e. for TELE-EDesC we used question-answer feedback format at decision making step which we referred as "DMTQ"while for informative visualisations same information was provided in text format.

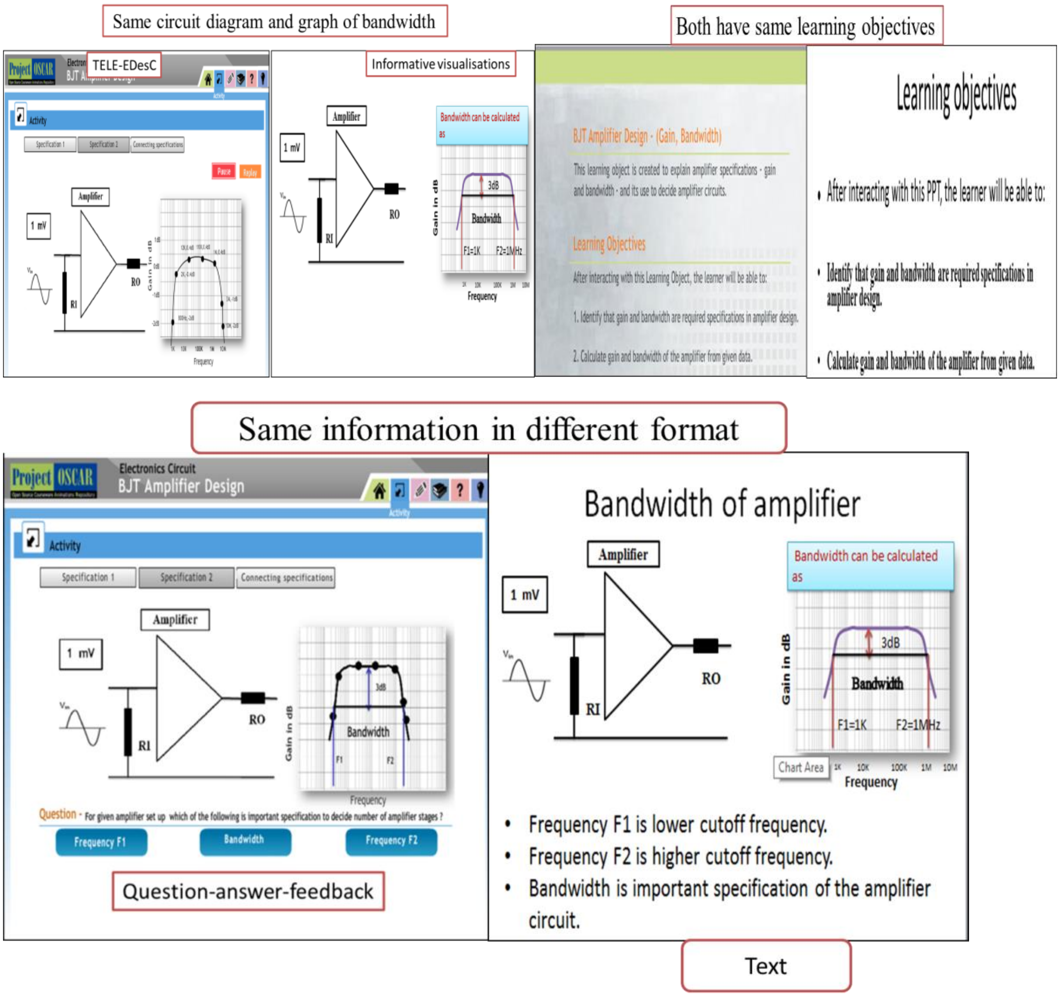


Fig. 6.2 Similarities and difference beteen TELE-EDesC and Informative visualisations

Informative visualisations contain interactive set of slides, diagrams and animations, but without the TELE-EDesC features of Decision Making Task Questions, Concept Clarification Questions, Controlled Animation, and Simulative Manipulation and so on. Screenshots of the learning material is attached in Appendix II.

Students were assigned to two groups using a process of random assignment. For the topic of DC circuit design, the experimental group consisted of 90 participants (43 male, 47 female) and the control group had 90 participants (44 male, 46 female). For the topic of Amplifier AC circuit, experimental group consisted of 28 participants (17 male, 11female) and control group consisted of 29 (18 male, 11 female). For the topic of OP-AMP comparator experimental group consisted of 27 (20 male, 07 female) and control group consisted of 30 participants (24 male, 06 female) The equivalence between the two groups for each topic was tested on basis of students' previous semester's marks for the course of analog electronics. Test included routine design problems and conceptual questions based on topics from analog electronics. No statistically significant difference was found between them (t=1.2, p=0.11).

Students in both groups worked with their respective material for 30 minutes, after which they were given the post-test. The post-test contained an open design question at the 'innovative' (Brown & Chandrasekaran, 1989) level. The design questions were based on the topic in the learning material in TELE-EDesC, but were not identical. For example, the post-test question asked students to design a circuit with different specifications than those in the learning materials, which enforced students to think about a different set of decisions. Students were given up to 30 minutes to work on the post-test, during which they wrote their detailed design (on paper). Fig. 6.3 shows the post-test design question structured by students.

- You are designing a project for class exhibition. In the project you measured signal which is weak signal with 10mV amplitude. You need to record this 10mV signal for further processing, but recorder need minimum 1 V signal to start recording. Thus you have to first amplify 10mV signal to 1V.The frequency range of the measured signal is 100Hz to 600 KHz. The circuit should not overload the recorder as well as should not get overloaded from input signal generator. Which circuit will you plan to design? Here you will only suggest your plan and not detailed circuit design. Off shelf active devices available to you are BJTS and FETS.Design plan of your circuit will include following (These are guidelines)
- The important specifications you will consider to design the circuit
- All important decisions related to circuit like selection of active devices, circuit configurations, number of stages etc with proper justification. (Why you suggest these circuits or devices or confg. etc.)
- Write the statement including all clearly stated specifications, circuit structures like devices, configurations etc. So that the statement can clearly guide designer to design the circuit. (e.g. I will design XYZ circuit containing XYZ devices and with XYZ specifications)

Fig. 6.3. Post-test Question for controlled experiment

6.1.3. Instrument

The rubrics developed and validated for SOP design competency (Chapter 4) were used to assess students' post-test responses to the design problem. As described in Section 4.4, the rubrics were tested for inter-rater reliability, which was found to be kappa = 0.73 for SOP competency. The rubrics contain a 4-point ordinal scale: Missing, Inadequate, Needs

Improvement and Target Performance. When the rubrics were used for students' formative assessment, the scale provided is as described. In addition, when the rubrics were used for research on students' attainment and progress of sub-competencies, scores were assigned for each level of the scale: Missing - 0, Inadequate -1, Needs Improvement - 2 and Target Performance -3. The rubrics for assessment of SOP are shown in Table 4.4, Chapter 4.

6.1.4. Data Analysis techniques

Students' responses to the design problem on the post-test were scored using the above rubrics. The performance of the experimental and control groups were compared using the following analyses:

1) Comparison of performance between students in two groups based on rubrics scores for SOP competency (Section 6.2.1)

Since the rubrics scores are ordinal data, the frequencies of students attaining different scores on the rubrics and the mean ranks of the two groups were compared for each sub-competency SOP1, SOP2, SOP3 and SOP4. The statistical significance of score difference between two groups was analysed using Mann-Whitney U-test. We compared SOP scores of control group students and experimental group students for different topics from analog electronics circuits.

2) The role of students' prior knowledge in their attainment of SOP sub-competencies. (Section 6.2.2)

Students from the experimental group were divided into three categories based on their previous test marks. These tests are traditional exams at the end of semester containing conceptual question and routine design problem. Students were stratified into three categories using percentile scores from their test marks. We labelled students in these categories as high, medium and low achievers based on their marks of a previous traditional test. Data analysis was carried out in multiple ways as follows:

a. Comparison between high, low, medium achievers from experimental group using Kruskal Wallis test on SOP sub-competency scores.

b. Comparison across groups - SOP sub-competency scores of low, medium, high achievers from both experimental group and corresponding achievers from control group

3) Relation between students' prior knowledge level and success in attaining SOP competency (Section 6.2.3)

Using the Stratified Attribute Tracking (SAT) diagram (Majumdar & Iyer, 2014), we investigated the relation between students' prior knowledge achievement level (low, medium, high categories) and how successful they were in attainment of SOP sub-competencies (based on rubrics scores). The SAT diagram is a visual representation that explicates trends in learning analytics data. It is a *"unified graph that enables tracking individual attribute values in a dataset and stratifying them according to criteria set by the researcher*" (Majumdar & Iyer, 2014). The 'attributes' can be considered to be the variables of interest, which in this case are students' prior knowledge level and success in attaining SOP competency. The 'strata' in this case were the categories of low, medium and high for prior knowledge level, and unsuccessful and successful in attainment of SOP sub-competencies. The SAT diagram also enables researchers to study transitions of samples between the categories across variables. For example, the SAT diagram can help answer questions such as "How many low achieving students were successful in attaining SOP competency", or, "Students from which prior knowledge achievement level make up the 'successful' category in SOP?

6.2. Results of quantitative method: Learning effectiveness

6.2.1. Comparing TELE-EDesC group and control group on SOP post-test

Figure 6.4 shows the frequency of students attaining rubrics scores of 0, 1, 2 and 3 on each SOP sub-competency, for all topics together (N=295).

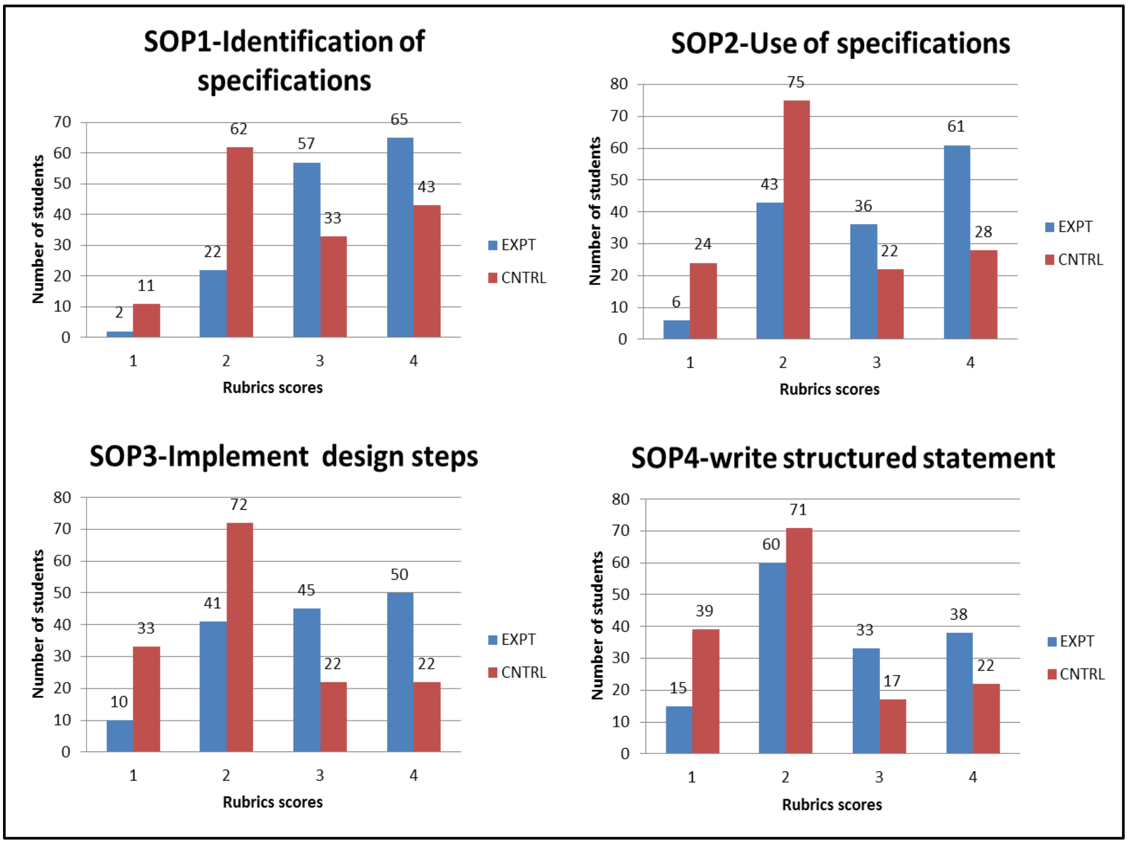


Fig. 6.4. Frequency plots of rubrics scores for experimental (N=146) and control group (N=149)

A visual inspection of the frequency plots shows that a larger fraction of students in the experimental group (TELE-EDesC group) have scores of 2 and 3 than students in the control group (informative visualisations group) for the same sub-competency (for example, see SOP2, scores 2 & 3). On the other hand, the lower rubrics scores of 0 and 1 contain more number of control group students than experimental group students.

The rubrics scores are an ordinal scale. That is, the scores of 0, 1, 2, and 3 are not uniformly spaced. The score of 0 (missing) or 1 (inadequate) indicate the student has not acquired the competency. On the other hand the score of 2 (needs improvement) or 3 (target) indicate that the student has partially or completely acquired the competency. The difference between 2 and 3 is small: Score of 2 means students started acquiring the competencies and some minor things are missing in the performance, while score of 3 means that the student acquired competencies perfectly. Thus we compare students who scored 0/1 versus those who scored 2/3. For SOP1 number of students who acquired score of 2 is (57) and who scored 3 are (65). Together total number is 122, i.e. 83% (122/146). Whereas, the number of students who scored 0 (22) or 1 (1 student) is total of 23, i.e. 16% (23/146).On similar lines analysis done for SOP2 shows that 66% students achieved score of 2 or 3 while 33 % achieved a score of 0 or 1. The analysis done for SOP3 shows that 65% students achieved score of 2or 3 while 34% students attained score of 0 or 1. This results shows that number of students reached to target or nearing targets are more than 60% and students not acquiring the competency are less than 40%.

To analyse this more rigorously, the mean ranks of the two groups are calculated. In Table 6.1, the mean ranks of the rubric scores of the experimental group and control group are shown. The mean ranks of the TELE-EDesC (experimental) group are higher than that of the informative visualisation (control) group. Students who worked with TELE-EDesC scored higher than students who studied using informative visualisations, and the score difference is statistically significant at p<0.01 level for each sub-competency SOP1, SOP2, SOP3 and SOP4.

Table 6.1. Comparison of SOP sub-competency ranks

Sub-competency	**Group**	**N**	**Mean rank**	**p-value**
SOP1	experimental	146	171.60	< 0.01
	Control	149	124.86	
SOP2	experimental	146	175.63	< 0.01
	Control	149	120.92	
SOP3	experimental	146	177.02	< 0.01
	Control	149	119.56	
SOP4	experimental	146	169.19	< 0.01
	Control	149	127.22	

We note that there is a statistically significant difference between the two groups for each sub-competency of SOP competency. From these we inferred that TELE-EDesC activities were useful to trigger SOP competency among students. Even though informative visualisation consisted of same content from the domain (but in a different format), students' were not able to apply SOP competency to given design problem.

We also examine the mean rubrics score (out of 4) for each sub-competency. No statistical tests of difference were performed on the mean rubrics score since the data cannot be strictly considered as interval. However, an examination of the actual score on the rubrics can give additional insight on students' performance level. Table 6.2 shows these data. From Table 6.2, we see that for each sub-competency, the experimental group mean was higher than the control group. Control group students scored low in SOP2 (1.3), SOP3 (1.2) and SOP4 (1.1). Since a rubrics score of 1 indicates that students' attainment of that sub-competency is 'Inadequate', mean scores near 1 indicate that students' have difficulty in the corresponding sub-competencies.

Table 6.2. Comparison of SOP sub-competency mean scores

Sub-competency	**Group**	**N**	**Mean rubrics score (out of 4)**
SOP1	experimental	146	2.26
	control	149	1.72
SOP2	experimental	146	2.04
	control	149	1.37
SOP3	experimental	146	1.92
	control	149	1.22
SOP4	experimental	146	1.65
	control	149	1.14

a. *Comparison of rubrics scores of experimental group and control group for different topics:*

The controlled experiments are carried out with three different topics from analog electronics course. Tables 6.3-6.5 show comparison of SOP sub-competency scores between control and experimental group topic wise (DC circuit design, amplifier design and OPAMP circuit design).

Table 6.3. Comparison of SOP sub-competency ranks for topic of DC circuit design

Sub-competencies	Group	N	Mean score	Mean Rank	p-value
SOP1	Expt	90	2.24	101.28	0.004
	Cntrl	90	1.81	80.6	
SOP2	Expt	90	2.12	112.77	<0.001
	Cntrl	90	1.12	68.98	
SOP3	Expt	90	1.70	110.36	<0.001
	Cntrl	90	0.82	71.41	
SOP4	Expt	90	1.14	102.31	0.0018
	Cntrl	90	0.71	79.55	

Table 6.4. Comparison of SOP sub-competency ranks for topic of Amplifier design

Sub-competencies	Group	N	Mean score	Mean Rank	p-value
SOP1	Expt	29	2.34	37.55	<0.001
	Cntrl	28	1.39	20.14	
SOP2	Expt	29	1.93	36.53	0.0001
	Cntrl	28	1.03	21.19	
SOP3	Expt	29	2	37.63	<.001
	Cntrl	28	0.96	20.05	
SOP4	Expt	29	1.86	34.67	0.004
	Cntrl	28	1.1	23.15	

Table 6.5. Comparison of SOP sub-competency ranks for topic of OP-AMP comparator

Sub-competencies	Group	N	Mean score	Mean Rank	p-value
SOP1	Expt	27	1.96	37.24	0.0004
	Cntrl	30	1.1	21.58	
SOP2	Expt	27	1.66	34.59	0.015
	Cntrl	30	1.1	23.97	
SOP3	Expt	27	1.51	34.91	0.011
	Cntrl	30	0.9	23.98	
SOP4	Expt	27	1.51	35.7	0.0004
	Cntrl	31	0.86	22.97	

For all the three topics we found statistically significant difference between SOP sub-competencies of experimental and control group. The scores for SOP1 sub-competency are similar for all the three topics, while for SOP2 sub-competency we found slight drop in the scores [DC circuit (2.12), Amplifier design (1.93) and OPAMP comparator (1.66)]. Topic complexity is progressively increased from DC circuit design to OP-AMP comparator. In first design topic single specification of Q point location and related design concepts are addressed, while in Amplifier design we combined three related specification and decision making process is little bit complex. In third topic of OPAMP comparator along with OPAMP concepts we added LED display design. For SOP4 we found improved score from topic 1 (DC circuit design) to topic 2 (Amplifier design).

6.2.2. Role of prior content knowledge in attainment of SOP competency

Table 6.6 shows SOP sub-competency mean ranks of high, medium and low achievers in TELE-EDesC experimental group, stratified according to their prior performance in a traditional content-focused test. The analysis is done on a subset of the total students, who studied topic DC circuit design & topic Amplifier Design. (N for this analysis = 90). These students are chosen for this analysis because they studied single course of analog electronics with fundamental concepts. Students who studied OPAMP topic are omitted from this analysis because these students are different from remaining sample in terms of prior knowledge level, as they have studied two courses on analog electronics circuits. Students who are selected for stratification studied single course of analog electronics circuits from same university.

Table 6.6. Performance in SOP sub-competency for low, medium and high achievers in experimental group

Group	**SOP1 (Mean rank)**	**SOP2 (Mean rank)**	**SOP3 (Mean rank)**	**SOP4 (Mean rank)**
Low achievers (N=33)	45.1	42.0	44.1	44.0
Medium achievers (N=30)	49	53.8	50.9	44.5
High achievers (N=27)	42.1	40.6	41.1	48.5
Chi-Square	1.01	4.53	2.14	0.51
p-value	0.6	0.1038	0.343	0.77

For all sub-competencies, mean ranks of low, medium and high achievers are comparable. The ranks in SOP1, SOP2 and SOP3 for high achievers are lower than the other two groups. There was no statistically significant difference found between the ranks of the three groups for all sub-competencies according to the Kruskal-Wallis test (at $p < 0.05$ level).

Tables 6.7 - 6.9 show comparison of SOP sub-competencies rubrics scores across the control and experimental groups for each achievement level of prior knowledge – low (6.7), medium (6.8) and high (6.9).

Table 6.7. SOP sub-competency in control vs. experimental group, low achievers

Sub-competencies	Group	N	Mean Rank	Mann-Whitney U	p-value
SOP1	Cntrl	30	26.91	342.5	0.026
	Expt	33	36.62		
SOP2	Cntrl	30	24.45	268.5	0.001
	Expt	33	38.86		
SOP3	Cntrl	30	24.05	256.5	<0.001
	Expt	33	39.22		
SOP 4	Cntrl	30	24.3	264	<0.001
	Expt	33	39		

Table 6.8. SOP sub-competency in control vs. experimental group, *medium* achievers

Sub-competencies	Group	N	Mean Rank	Mann-Whitney U	p-value
SOP1	Cntrl	30	26.23	322	0.04
	Expt	30	34.76		
SOP2	Cntrl	30	21.45	178.5	<0.001
	Expt	30	39.55		
SOP3	Cntrl	30	21.61	183.5	<0.001
	Expt	30	39.38		
SOP 4	Cntrl	30	28	375	0.23
	Expt	30	33		

Table 6.9. SOP sub-competency in control vs. experimental group, high achievers

Sub-competencies	Group	N	Mean Rank	Mann-Whitney U	p-value
SOP1	Cntrl	29	24.15	265.5	0.028
	Expt	27	33.16		
SOP2	Cntrl	29	23.13	236	0.007
	Expt	27	34.25		
SOP3	Cntrl	29	22.77	225.5	0.004
	Expt	27	34.64		
SOP 4	Cntrl	29	24.87	286.5	0.072
	Expt	27	32.38		

For low achievers there is statistically significant difference in SOP1 ($p < 0.05$ level), SOP2 ($p < 0.01$ level), SOP3 ($p < 0.01$ level), and SOP4 ($p < 0.001$ level) sub-competencies between control and experimental group. For medium achievers there is statistically significant difference in SOP1 (<0.05), SOP2, SOP3 sub-competency scores at $p<0.001$ level but no statistically significant difference in SOP4 at $p<0.05$ level. For high achievers there is statistically significant difference in SOP1 ($p < 0.05$ level), SOP2 ($p < 0.01$ level) and SOP3 ($p < 0.01$ level) sub-competency scores but no statistically significant difference in SOP4 at $p<0.05$ level.

The overall findings from the analysis of Tables 6.6-6.9 indicated that the sub-competency scores did not differ based on prior achievement level for students' in the experimental group. But when comparison is done between achievers of the same level across the experimental and control groups, it was found that low achievers showed difference in all sub-competencies, but in medium and high achievers difference was not significant for sub-competency SOP4. This means that only one category of students – those with low prior knowledge achievement level showed a statistical significant difference in SOP4. Roughly two-thirds of students, the medium and high prior knowledge achievers, in the experimental group scored low on SOP4, similar to their counterparts in the control group.

6.2.3. Identification of successful students from achievers category for each sub-competency

The statistical tests of significant difference of SOP sub-competency scores (Table 6.1) showed that there is a significant difference between students in the experimental group and control group in all sub-competencies. Further, we categorized students into low, medium and high achievement levels based on prior content knowledge and found that the rubrics scores on SOP design sub-competencies were statistically similar for students of all prior achievement levels (Tables 6.6-6.9). In other words, regardless of whether a student is a low, medium or high achiever in terms of prior knowledge, there is no difference in whether he or she is *successful or unsuccessful* in design. Here, students with rubrics scores of 0 or 1 were considered as unsuccessful in that sub-competency while students with scores of 2 or 3 were considered as successful.

We now investigate *who* was successful in attaining SOP competency. That is, students from what achievement levels of prior knowledge are present in the 'successful' category of SOP design competency of the experimental group. This analysis is performed using the Stratified Attribute Tracking (SAT) diagram (Majumdar & Iyer, 2014). This diagram is a relational representation between two variables - students' prior knowledge achievement level and their success in SOP competency. Each variable is represented in a column, and each column contains the categories within that variable: prior knowledge achievement level – low, medium, high; and success in SOP competency – unsuccessful and successful. These are connected by relational lines which represent the number of students moving from one column to another.

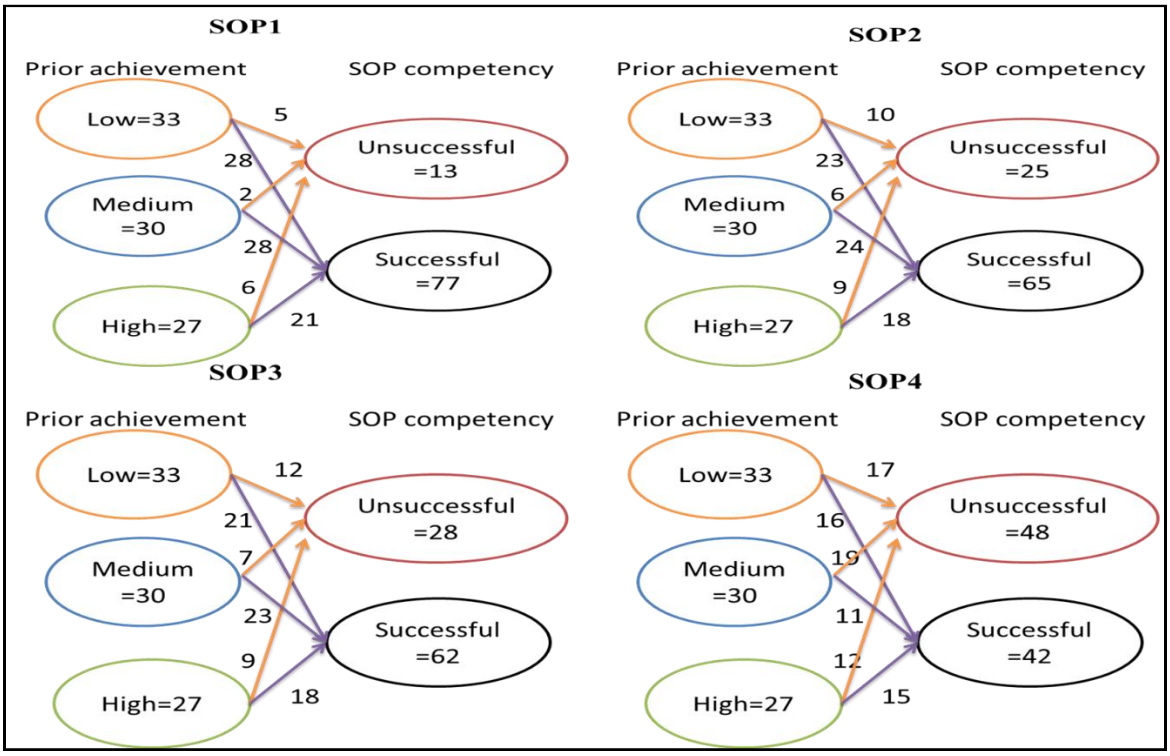


Fig. 6.5. SAT diagram showing relation between prior knowledge achievement level and success in SOP competency

Fig. 6.5 presents the SAT diagram for all SOP sub-competencies for experimental group that is, the relation between two variables of students' prior knowledge achievement level and their success in SOP competency. We examine students who worked on topic of DC circuit and amplifier design (N=90) for this analysis. In the experimental group more number of students were categorised as *successful* students on SOP sub-competencies SOP1, SOP2 and SOP3. But for SOP4 it was found that a large fraction experimental group students from were unsuccessful. This was true of students from all prior achievement levels leading to a conclusion that students' prior achievement level did not play a role in the attainment of SOP competency.

6.2.4. Summary of learning effectiveness results from quantitative strand

The quantitative data analysis of post-test experiment can be summarized as follows: Students who studied using TELE-EDesC scored high on all sub-competencies compared to students who studied using informative visualisation. Students from experimental and control group were each categorised into low, medium and high achievers based on prior scores on a content-based test of electronics subject. It was found that there was no significant difference in attainment of SOP sub-competency between students of different prior knowledge achievement levels in both the experimental and the control group. Attainment of SOP4 seems to be hard for all students.

6.3. Explaining quantitative results: designing the qualitative study

The previous section showed that TELE-EDesC helped students to attain SOP sub-competencies more effectively than control group students who learnt via informative visualization. It was also found that attainment of SOP4 – writing structured problem - was difficult for all students, including those who learnt via TELE-EDesC. However, the quantitative study was not designed to answer questions of how or why TELE-EDesC was effective. The likely mechanism for the effectiveness of TELE-EDesC learning material lies in its pedagogical design described in Chapter 5. In this qualitative strand, we directly address the question of what makes TELE-EDesC effective, by examining students' behaviour as they interacted with TELE-EDesC.We conducted qualitative interaction analysis (Dettori, & Persico, 2008) of students interaction with TELE-EDesC. The research goal of this method is to identify behavioural differences between successful and unsuccessful students within the experimental group. We focus on students who learn with TELE-EDesC, and examine the patterns of interaction and self-learning behaviours of students who are successful in attaining SOP sub-competencies in the open design problem in the post-test, and those who were not.

6.3.1. Participants and procedure

The participants in this qualitative study were a subset of the experimental group of the quantitative study. 10 students from the experimental group who learnt with TELE-EDesC in the module of ‘DC circuit design’ were selected for this study. Purposive sampling was conducted to obtain 5 participants who scored high on the post-test in the control study, and 5 who scored low on the basis of the SOP competency rubrics. Students with average rubrics scores of 0 or 1 on relevant competencies were identified as low scorers or unsuccessful and those with scores of 2 or 3 were considered to be high scorers, or successful. However, the two groups were found to be equivalent on previous exams that tested conceptual understanding and traditional problem-solving, that is, they were all in the medium category of prior knowledge achievement level.

While students interacted with the material, their screen activities were captured by Camstudio (www.camstudio.org) screen-recording software. These recordings were transcribed, coded and analysed to get an insight into students’ behaviour when they learn with self-study TELE-EDesC.

6.3.2. Data coding

Camstudio recordings of each student were first transcribed. The transcripts were segmented by Learning Dialogs in the learning material, and focused on start time, end time, Dialog in the learning material and the action taken by student while interacting with the content. An example of a transcript is shown in Table 6.10.

Table 6.10. Example of transcript of Camstudio recording

Start time (min)	**End time (min)**	**Content in the learning material**	**Student's actions**
0.15	0.21	Concept of faithful amplification	Read
0.21	0.34	Faithful amplification - CCQ Which of the following waveforms represent faithful amplification?	Question read and 4th option clicked. Feedback read Next Activity button clicked
……	…….	…………..	…………………
0.47	1.31	DMTQ1- Question to identify DC circuit For the given CE amplifier circuit identify which is appropriate DC circuit?	Question read, 2nd option clicked Feedback read, wrong answer. Try again button clicked 3rd option clicked
……	……	…………..	…………………
12.11	13.11	Variation in Q-point with radio buttons to vary current	Clicked Vary Q-point button Clicked button at 10µA Clicked button at 20 µA

Table 6.11. Coding scheme applied to transcript of Camstudio recording.

Learning Dialogs	**Students' behaviour pattern**	**Code**
Information agents ,Capsule Recommendations	Read	Read-concpt Read-Info
Decision making task question (DMTQ) Concept clarification questions (CCQ)	Click the answer	Clk
	If answer is correct, go to Next	ClkNext-Cor
	If answer is wrong, click on some other answer	ClkNext-Wrg
	If answer is correct click on some other answer	ClkOther-Cor
Simulative manipulation	Manipulate few variables	SM-few
	Manipulate all variables	SM-all
Animation	View animation	ViewAnm
All functions	Revisit all slides	RV-conc, RV-info, RV-DMTQ, RV-CCQ, RV-VM

While learning from the TELE-EDesC, possible actions of students are: reading (*Capsule Recommendations*, *Information agents*) clicking correct or wrong answers, reading feedback to answers, re-trying the question, viewing the animation, and interacting with the variables in the simulation. Based on these actions, we assigned codes to students' interactions with the TELE-EDesC material (Fig. 6.11).

6.3.3. Data analysis techniques

The main research goal was to investigate differences in the behaviour pattern of unsuccessful and successful students on the SOP rubrics, as they interacted with the TELE-EDesC learning materials. This difference was characterized on multiple measures. We first analysed how each student spends his/her time during the self-learning process. We then compared the duration of time spent by unsuccessful and successful groups on different Learning Dialogs in the TELE-EDesC. To compare behaviours across students who spent different amounts of total time, we calculated the percent of time spent per learning dialog out of the total learning time. The second parameter measured was the frequency of visits for each learning dialog. The time spent on each learning dialog and the number of revisits indicates the emphasis a student places on different TELE-EDesC Learning Dialogs in her learning process. The third measure was to identify the correlation between the post-test scores of students and the time spent for Learning Dialogs. Finally, we analyse the chronological sequence of actions of a typical student from each group as a graphical representation of the timeline of their learning process.

6.4. Results of qualitative study

6.4.1. Time spent on Learning Dialogs

The time spent by students on the TELE-EDesC range from 8 to 23 minutes, with a mean time of 19.2 min. (SD=4.4min.) by successful learners and 15.6 min. (SD=4.7 min) by the unsuccessful learners. Successful learners spent maximum time on Decision Making Task Questions (4.5 min), followed by reading activity (3.5min), viewing controlled animation (3min) and simulative manipulation (2.8 min). Unsuccessful learners on the other hand spent maximum time on reading activity (3.5 min) followed by Concept Clarification Questions (2.3 min). The largest difference was in the time spent on controlled animation (high – 3min., low – 0.68 min) and simulative manipulation (high – 2.8 min, low – 0.26 min). Fig. 6.6 shows the comparison of time spent on different activities by successful and unsuccessful learners.

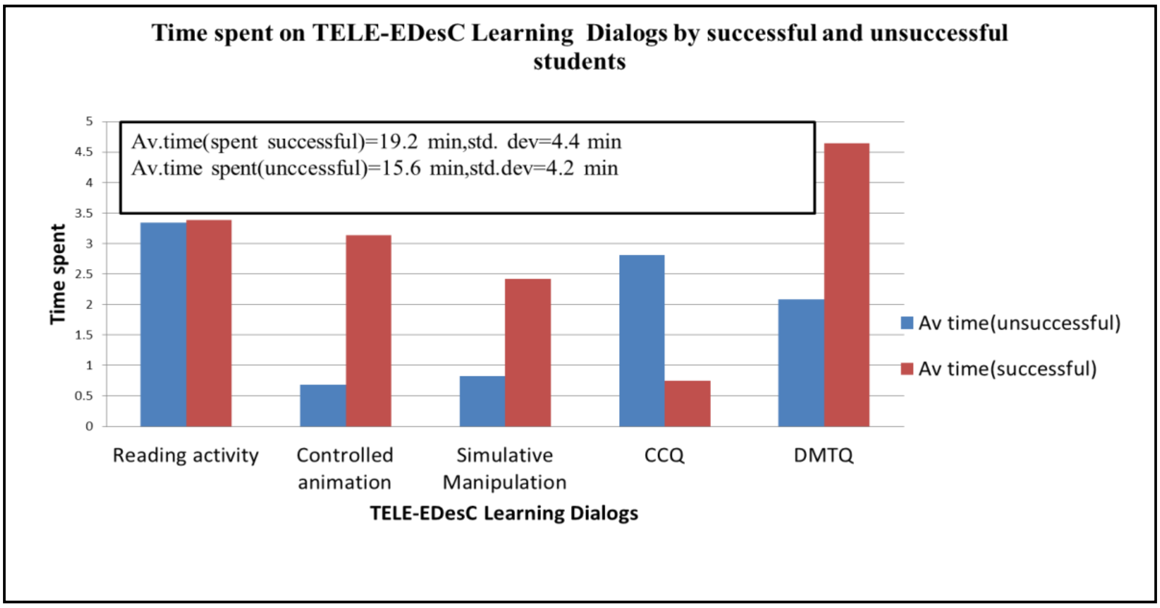


Fig. 6.6. Comparison of total time spent on TELE-EDesC activities by successful and unsuccessful students

As shown in Fig. 6.7, DMTQ is most preferred learning dialog for successful students; they spent 32% of their learning time on DMTQ, while unsuccessful students spent only 22% of their time. For simulative manipulation successful students spent 17% time while unsuccessful students spent 8% time. Among unsuccessful students, reading is most preferred activity in which they spent 34% of their learning time while successful students spent 24% of their time. The second preferred learning dialog for unsuccessful students was CCQ; they spent 29% of the learning time on CCQ, while successful students spent only 5% time in CCQ.

The most frequently visited learning dialog by both group students is the DMTQ followed by Reading and viewing animation are the next most frequently visited Learning Dialogs by both groups. The main difference in behaviour of visits is in Simulative Manipulation, which is visited by successful students more than unsuccessful , and CCQ which is more frequently visited by unsuccessful than successful students.

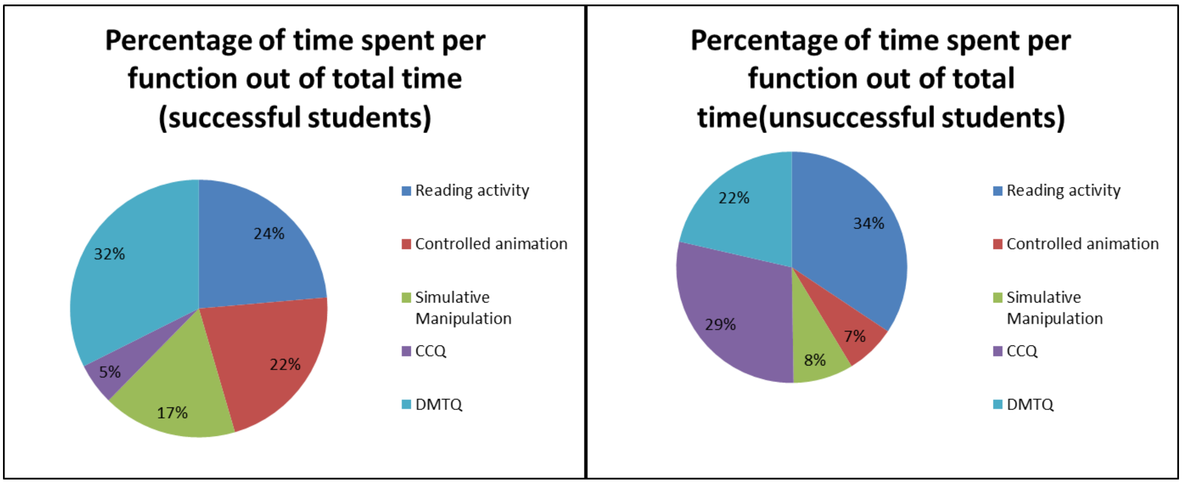


Fig. 6.7. Percentage time spent on each learning dialog by successful and unsuccessful students

Table 6.12 shows a correlation analysis between post-test SOP scores and time spent on different Learning Dialogs.

Table 6.12. Spearman rank correlation coefficient between SOP scores and time spent on different Learning Dialogs (* indicates significance at 0.05 level)

Time spent on Learning Dialogs	**Total time**	**DMTQ**	**CANM**	**SM**	**CCQ**
Post-test SOP scores	0.485	0.674*	0.654*	0.6	-0.734*

There is positive and significant correlation (ρ=0.67) between post-test scores and time spent on DMTQ as well as time spent on animation (ρ=0.65). We also found positive but non-significant correlation between post-test scores and time spent on simulative manipulation (0.6). CCQ activity time is significantly negatively correlated with post-test scores (ρ=-0.73).

6.4.2. Chronological representation of learning behaviour

We illustrate the learning pattern of students interacting with TELE-EDesC with an example each of typical unsuccessful and successful students. Figs. 6.8 and 6.9 show the timelines of behaviour for unsuccessful and successful students. Time is presented from left to right (in minutes), and each row represents a different Learning Dialogs in TELE-EDesC. When a student spends time on an activity, a block is placed on the row for that activity for the duration of time spent. The length of the block is proportional to the amount of time spent for that activity. This representation is adapted from the analysis in (Atman et. al., 1999) and is similar to the chronological representation of discourse (Hmelo-Silver et. al., 2009).

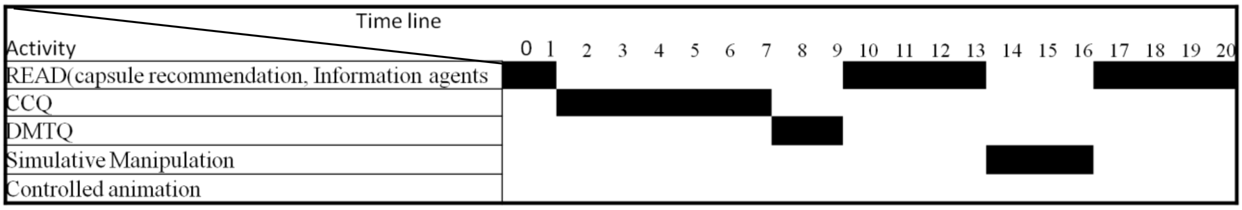


Fig. 6.8. Activity time line for unsuccessful student (student A)

As shown in Figure 6.8, Student A, an unsuccessful on task, (post-test score = 2.5/ 12) spent 20 minutes on the learning material, most of it on the reading activity. In CCQ and DMTQ activities, student A clicked the correct answer and proceeded to the next activity without reading feedback. In the simulative manipulation activity, student A interacted with the simulation for only one value of the parameter. For the other values, he advanced through the material without viewing the feedback.

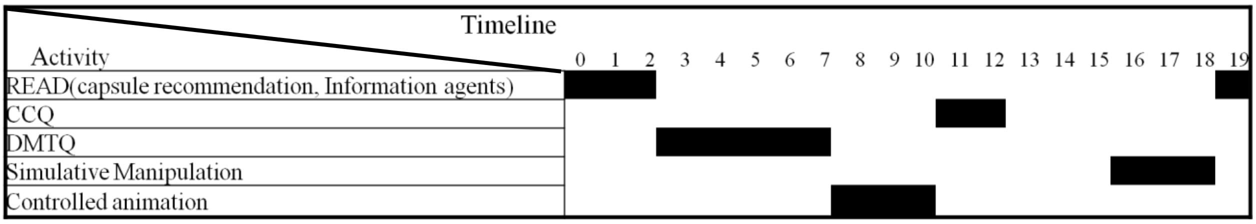


Fig. 6.9. Activity timeline for successful student (student B)

Student B, a student who is successful on task (post-test score =11/ 12) spent 19 minutes on the TELE-EDesC. She spent the least time in reading the material (1 minute) and proceeded to DMTQ activity. In DMTQ activity, she first attempted the first question correctly and proceeded to next DMTQ for which selected the wrong answer, read the feedback and attempted the question again. This time she selected the correct answer. For the third DMTQ she selected the correct answer and then read the feedback for all answers, spending a total of 5 minutes on this activity. When interacting with the simulation, student B manipulated the values of all available variables, observed the corresponding changes in the circuit.

6.4.3. Discussion of qualitative study results

Comparison of self-learning behaviour of unsuccessful and successful students on SOP task showed differences in all the measures used. Successful students mainly focused on Learning Dialogs such as experimenting with variables in the simulation and Decision Making Tasks Questions. They not only spent more time on these Learning Dialogs but also revisited it multiple times. On the other hand, unsuccessful spent the largest fraction of their learning time reading material and attempting concept clarification questions. Learning time spent on simulative manipulation is low for this group. In terms of similarities between the two groups, there was no significant difference in the total time spent on learning material. Similar behaviour for both groups was also observed in the reading of concepts, Information agents and Capsule Recommendations. While the number of visits to DMTQs was seen to be nearly equal for both groups, the fraction of learning time spent on these activities is different. The results of the correlational analysis (Table 6.11) are consistent, in that SOP scores correlates positively with time spent on DMTQ activity.

This qualitative learning behaviour study gave insight on the productive learning behaviours of who worked with the Learning Dialogs of TELE-EDesC. Successful students were found to first make incorrect decisions in DMTQ, then studied feedback and repeatedly attempted the decision making task, spending time on the feedback for each choice. For Simulative Manipulation tasks, successful students selected and manipulated all variables available and read feedback for each of them. Students who used same material as tutorial just to answer question and did not read feedback, or used only few variations or spent time reading information from Information Agents, could not perform the design tasks successfully.

Overall, students who scored low (unsuccessful) on the SOP competencies have used the TELE-EDesC learning material in a more traditional manner, mostly as reading information and clarifying concepts. On the other hand, the successful students on SOP competencies have used the material in a more *active* manner, by performing activities such as acting on feedback, examining implications of different alternatives in the decision making tasks and working through all possible variable manipulations in the simulation. Since there is no significant difference between prior knowledge levels between two groups, it is unlikely that low entry level knowledge led to this behaviour of the low scoring group.

The motivation for conducting this comparative study was to try to get an insight into the relation between learners' behaviour as they interact with self-learning material, and the quality of their learning. Naps et al. (Naps et al., 2002) recommends that interactive visualizations will be beneficial if the learner is active in the learning process. Students who are successful in attaining SOP competencies employ an active learning process in which they are engaged with the Learning Dialogs at a high level. On the other hand, the engagement level of unsuccessful students is lower, with reading being the primary mode of interaction. In TELE-EDesC, the purpose of developing Learning Dialogs is to provide two way communications between learner and environment. Thus students who used this reciprocative activity to full extent are successful on SOP task.

6.5. Discussion

The TELE-EDesC testing process was carried out using a two-step sequential explanatory mixed method. The first step consisting of a quantitative study led to results of learning effectiveness of TELE-EDesC compared to informative visualisations. TELE-EDesC was effective in developing SOP sub-competencies among students. However all students of all achievement levels were challenged in the attainment of SOP4 – write structure problem statement.

The attainment of students' SOP competencies from TELE-EDesC was further studied in the second step qualitatively by analysing screen shots of their behaviour with TELE-EDesC. It was found out that students who were unsuccessful on design task skipped some of the important activities of TELE-EDesC and tried to study TELE-EDesC as tutorial material. But students who were successful on design task tried to use it as active learning material which further translated into successful completion of given task. This shows productive learning behaviour of successful students.

The qualitative learning behaviour study showed that students who studied the Learning Dialogs of TELE-EDesC were the students successful on design tasks. Successful students were found to first make incorrect decisions in DMTQ, then studied feedback and repeatedly attempted the decision making task, spending time on the feedback for each choice. For Simulative Manipulation tasks, successful students selected and manipulated all variables available and read feedback for each of them. Students who used same material as tutorial just to answer question and did not read feedback, or used only few variations or spent time reading information from information agents, could not perform the design tasks successfully. Thus quantitative and qualitative analysis confirmed that TELE-EDesC activities triggered essential cognitive processes to develop Structure Open Problem competency. Students' success in being able to structure the open problem in the post-test did not depend on their prior knowledge achievement level, but dependent on their learning behaviours as they interacted with TELE-EDesC.

The development of TELE-EDesC was based on recommended principles from educational research such as formative assessment. Activities such as DMTQs promote self-regulated learning through the feedback, which not only indicates the correct or wrong answer, but guides the learner from the actual performance towards the desired performance (Nicol, 2007). We found that time spent by learners on the DMTQ activity is correlated with post-test scores which indicates the usefulness of DMTQ activity in self-learning material. The high scorers on the post-test, i.e. the successful learners also spent more time on Simulation Manipulation wherein for every change in the variable, visual and textual feedback is provided. Chen et.al recommended (Chen et. al.2011) such 'Simulative Manipulation' activities to help the learner to acquire knowledge through process of experimentation, exploration and reflection. All these Learning Dialogs which were developed based on design thinking skill aspects triggered essential metacognitive processes amongst students.

The aim of this testing process was to test if the Learning Dialogs of TELE-EDesC promote the development of SOP sub-competencies. All sub-competencies showed improvement in scores, but attainment of SOP4 was less compared to other sub-competencies attainment even in TELE-EDesC group. Further learning behaviour study shed light on attainment of competencies. The student's responsive communication is important to develop SOP competency among students. This further guided us to include Learning Dialogs which may propagate the productive learning behaviour among students. SOP 4 which was seen little difficult also need to be developed through TELE-EDesC.

SOP4 integrates the learning from all other sub-competencies of Structure Open Problem – SOP1, 2, and 3 - leading to the need for a synthesis process among students. The development of SOP4 indicates students are able to perform synthesis of overall unstructured problems through decision making, concept integration. Thus it is key sub-competency. We thus refined TELE-EDesC to guide students to learn with TELE-EDesC effectively and able to integrate the learning processes of SOP4.

6.6. Summary

In this chapter we described the process of testing of TELE-EDesC through controlled experiment with students. We found that the experimental group students who learnt using TELE-EDesC scored high on all sub-competencies compared to the control group students who studied using design based informative visualisations. Further detailed analysis of data through the SAT diagrams showed that prior achievement on the course of electronics did not play a role in the attainment of SOP sub-competencies. The qualitative learning behaviour study showed that students who interacted with all the Learning Dialogs of TELE-EDesC were the students successful on the post-test open design tasks. Thus quantitative and qualitative analysis confirmed that TELE-EDesC Learning Dialogs triggered essential metacognitive processes to develop SOP. It is essential to propagate two way communication between learner and system by guiding learners. It is also required to help learners to develop synthesis process effectively to attain SOP4. Chapter 7 describes the refinement of TELE-EDesC to trigger productive learning behaviour amongst learners.

Chapter 7

Refining TELE-EDesC via self-assessment rubrics

Chapter 5 described the development of a pedagogical framework and TELE-EDesC environment to teach structure open problem (SOP) design competency. Learning Dialogs such as Decision Making Task Questions (DMTQ), Concept Clarification Questions (CCQ), Simulative Manipulation (SM) and Capsule Recommendations, were designed in TELE-EDesC to target students' attainment of the SOP sub-competencies, namely, identification of specifications (SOP1), use of specifications (SOP2), and sequencing of steps (SOP3), and writing design statement (SOP4).

Chapter 6 contained the evaluation of TELE-EDesC modules in topics of analog electronics. Through empirical studies, we analysed students' progress of attainment of SOP sub-competencies. We found that for all sub-competencies SOP1, SOP2, SOP3, SOP4, the scores of experimental group students on an open design problem post-test were statistically significantly higher than control group students. Further we studied difference in learning behaviour of successful and unsuccessful students with TELE-EDesC. We found that successful students interacted with all the Learning Dialog actively and responded to different types of feedback provided by system to their actions. On the other hand, unsuccessful students interacted with Learning Dialogs as material to get through, that is, they performed part of the activity stated (such as they manipulated some variables in a simulation, or chose one answer in a DMTQ), but did not read the feedback or revise their interaction based on it. This study directed us to need to refine TELE-EDesC, so that all students can be guided to reciprocate to the essential Learning Dialogs of TELE-EDesC.

7.1. Theoretical basis for refinement of TELE-EDesC

The objective to refine TELE-EDesC was to guide students to apply all the Learning Dialogs of TELE-EDesC efficiently and actively. One of the ways to enhance learning is applying "assessment for learning" (Dochy, Gijbels & Segers, 2006). If students are guided using transparent assessment criteria then they may apply productive learning behaviour and study Learning Dialogs effectively. Rubrics have been suggested as one of the instruments to enhance deep learning amongst students by providing rich, detailed and specific feedback to students about their performance (Arter & McTighe, 2001; Wiggins, 1998). They encourage self-learning as rubrics provide formative feedback not only at the target level of performance, but also at all intermediate levels. They help students to assess their own efforts relative to the target criteria. The goal of rubrics is for students understand the target concept or ability they are expected to achieve and the criteria to achieve that ability. It is also mentioned that if students are given an opportunity to apply rubrics to their work they acquire the desired abilities (Etkina et al., 2006). Rubrics is thus helpful for students to self –tune their learning process (Nicole, 2007) to attain desired outcomes.

The assessment rubrics for engineering design competencies that we developed earlier (Chapter 4) can thus be added to TELE-EDesC. Thus, in the refined version of TELE-EDesC, these rubrics are now included within the TELE-EDesC modules *explicitly* to implement formative assessment (Black & William, 1998). Students use the rubrics for self-assessment at various points in their interaction with TELE-EDesC. The rubrics provide students feedback on their responses to the TELE-EDesC learning dialogs, so that they can monitor their learning process themselves with respect to the learning goals. At the same time, they focus students' attention on the important cognitive processes needed for accomplishing the complex task at hand.

An important goal of TELE-EDesC is to support students to trigger the essential metacognitive processes needed to develop engineering design competencies, through Learning Dialogs. To show productive learning behaviour students should be able to proactively interact with the Learning Dialogs. Self-assessment rubrics is one such Learning Dialog which will guide learner to tune their learning process and assess self-learning. It will help learner to manage learning through planning, monitoring and evaluation the essential components of metacognition.

7.2. Refined TELE-EDesC

TELE-EDesC learning modules were refined by adding self-assessment rubrics as the learning dialogs. These rubrics are descriptive rating scales which consist of pre-established criteria to evaluate students' performance on each design sub-competency. The rubrics included for the sub-competencies related to SOP competency were shown in Chapter 4 (Table 4.4) and are reproduced in Table 7.1.

Table 7.1. Rubrics for sub-competencies of Structure Open Problem competency

SOP sub-competencies	**Target performance**	**Needs improvement**	**Inadequate**	**Missing**
SOP1: Is able to extract relevant specifications from given open ended problem	All relevant visible and hidden specifications are identified and interpreted accurately. No irrelevant specifications identified.	An attempt is made to identify specification Most of them identified but few hidden ones missing or needs more interpretation.	An attempt is made but specifications identified are most of them are wrong or irrelevant or incomplete.	No attempt is made to extract specifications
Is able to structure open problem using specifications	Specifications are used to identify interconnections of the system in order to structure problem.	An attempt is made to use specifications but minor specifications are not used, or used incorrectly.	An attempt is made to use specifications but required specifications not used or wrongly applied.	No attempt is made to use specification to structure problem
Is able to sequence the design steps based on specifications	All major and minor design steps are identified and sequenced correctly based on specifications.	Most designs steps are sequenced correctly. Few steps are missing or not sequenced correctly.	Design steps are not sequenced at all or not based on specifications.	No attempt is made to write design steps.
Is able to write structured design problem statement	Problem statement is written clearly including details of specifications and design steps.	Problem statement is written clearly but few minor details are missing.	Problem statement is not written clearly but scattered information is available.	No attempt to write coherent statement.

After interacting with Learning Dialogs such as Decision Making Task Questions and Concept Clarification Questions, students are provided the rubrics relevant to those activities. Since the rubrics contain descriptors not only of the target performance level, but also of non-ideal performance, they prompt students to carry out formative assessment of their own performance in the activity, and correct themselves if necessary. This helps students not only to monitor their level of achievement of cognitive task, but also plan learning based on expected target level. Fig. 7.1 shows the screenshots for the TELE-EDesC activities after adding Rubrics.

Self-assessment rubrics are provided after students respond to a question or interact with a Learning Dialog. When students respond, a reason-based explanatory feedback is provided and they are asked to rate their response. The assessment criteria which is the basis of score is also displayed. The criteria shows that where students are and how they can reach to target performance.

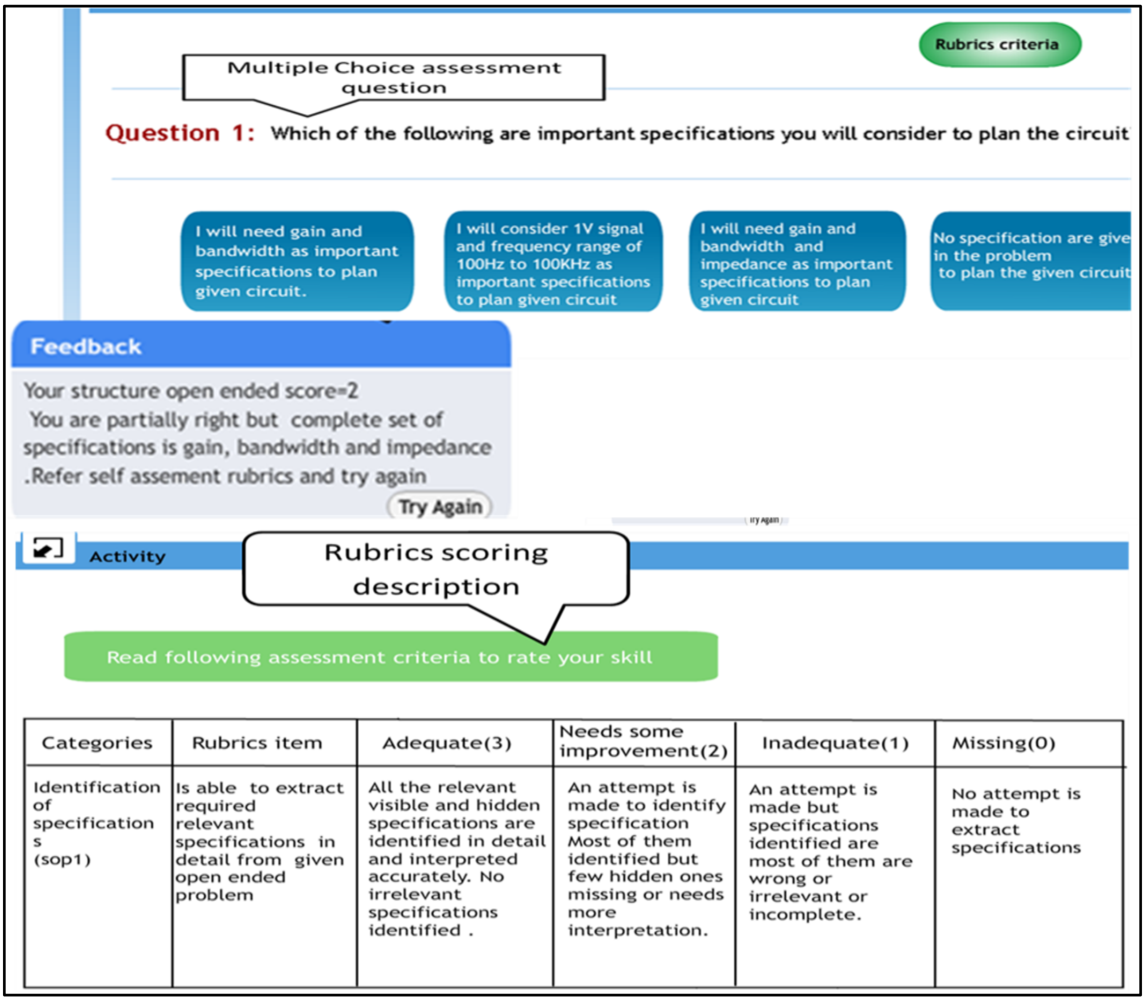


Fig.7.1. Screenshot of TELE-EDesC with self-assessment rubrics

7.3. Learning effectiveness of refined TELE-EDesC

We tested role of including self-assessment rubrics to TELE-EDesC, in the development of sub-competencies. We measured the learning effectiveness through a controlled experiment with conditions of including and not including rubrics within TELE-EDesC (sections 7.3.1 and 7.3.2). TELE-EDesC Learning Dialogs in both conditions are same except addition of rubrics for experimental group.

7.3.1. Learning effectiveness for attainment of SOP4

A two-group quasi-experiment was conducted to investigate the effect of including self-assessment rubrics into TELE-EDesC learning dialogs. The two conditions in the experiment were the presence or absence of self-assessment rubrics in the TELE-EDesC.

***Participants*.** The study participants were students from 2nd year Electronics Engineering (N=45) major. Students were familiar with technology-enhanced learning environments, as well as the content in the TELE-EDesC, as they had learnt the topic (Amplifier design) in their theory course. However, they were not exposed to design in this topic.

***Procedure*.** Students were randomly assigned to one of two groups. The control (TELE-EDesC) group had 22 participants and the experimental group (TELE-EDesC with rubrics) consisted of 23 participants. The equivalence between the groups was tested on basis of their previous semester's grades and no statistically significant difference was found between them (t=-0.08, p=0.9). Two sets instructional materials on the topic of amplifier design from electronics domain were developed. The control group received the same TELE-EDesC but without the self-assessment rubrics (these materials were similar to the ones described in Chapter 5, and used in Chapter 6 for the experimental group in the study in Section 6.2.2). The experimental group received TELE-EDesC which contained self-assessment rubrics, i.e. it had additional self-assessment rubrics added to the materials received by the control group. Students in both groups studied their material for 30 minutes, after which they attempted the post-test. The post-test contained an open design question on a topic related to (but not the same as) the instructional material for which students had to describe (on paper) their design.

Instrument. To assess the development of students' design competencies we used assessment rubrics, similar to the self-assessment rubrics as shown in table 7.1. These rubrics were validated prior to the experiment. Inter-rater reliability was found to give 75 % agreement (kappa value=0.61) between 3 instructors.

7.3.2. Data analysis and results

We calculated mean ranks and mean scores for sub-competencies for both the groups. Mann-Whitney test is carried out to know the statistical difference between two groups. Table 7.2 shows mean ranks for TELE-EDesC and TELE-EDesC with rubrics group

Table 7.2. Comparison of SOP sub-competency ranks

Sub-competency	**Group**	**N**	**Mean score**	**Mean rank**	**Z score**	**p-value**
SOP1	TELE-EDesC	22	2.68	20.76	-0.9281	0.35
	TELE-EDesC with Rubrics	23	2.85	24.4		
SOP2	TELE-EDesC	22	2.39	21.8	-0.3642	0.71
	TELE-EDesC with Rubrics	23	2.52	23.6		
SOP3	TELE-EDesC	22	2.39	20.93	-0.8341	0.40
	TELE-EDesC with Rubrics	23	2.61	24.21		
SOP4	TELE-EDesC	22	2.3	21.8	-0.3642	0.71
	TELE-EDesC with Rubrics	23	2.42	23.26		

The mean scores and mean ranks of TELE-EDesC with rubrics group are higher than the only-TELE-EDesC group. Mann-Whitney test indicated that the difference between the SOP ranks of TELE-EDesC and TELE-EDesC with rubrics is not significant (SOP1 (0.3>0.05); SOP2 (0.7>0.05); SOP3 (0.4>0.05); SOP4 (0.7>0.05)). Even though there is increase in mean scores for all sub-competencies we did not find significant difference in the mean rubrics scores.

We then applied examined how many students from each group could be categorized as "successful" in the post-test. Students with rubrics scores of 0 or 1 were considered as unsuccessful in that sub-competency while students with scores of 2 or 3 were considered as successful. This analysis is performed using the Stratified Attribute Tracking (SAT) diagram (Majumdar & Iyer, 2014). This diagram is a relational representation between two variables – the treatment group and their success in SOP competency. Each variable is represented in a column, and each column contains the categories within that variable: treatment group – control (TELE-EDesC), experimental (TELE-EDesC with rubrics); and success in SOP competency – unsuccessful and successful. These are connected by relational lines which represent the number of students moving from one column to another (Fig. 7.2).

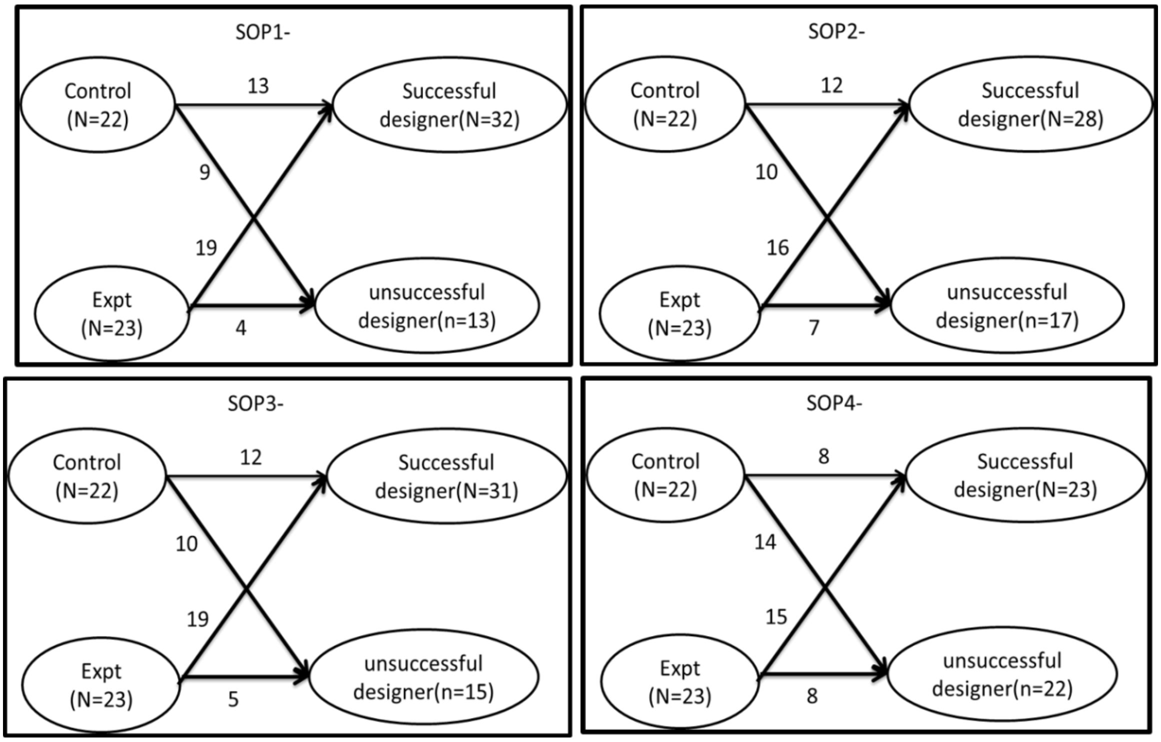


Fig. 7.2. Stratified Attribute Tracking Diagram for successful and unsuccessful design

We found that for the sub-competencies of ‘identify specifications in open problem’ (SOP1), ‘use specifications to structure problem’ (SOP 2) and sequence steps of design process (SOP3), more number of students fall in successful designer category both groups. Careful observation showed that more number of students from experimental group (for SOP1 19/23) contributed to successful designer category than control group students (for SOP1 13/22). Further for the sub-competency of ‘write structured problem statement’ (SOP4), we found that more number of students from control group (only TELE-EDesC) lie in unsuccessful category (14) than successful category (8). But in the experimental group (TELE-EDesC + Rubrics) more students (15) fall in successful category compared to unsuccessful (08). We can infer that SOP4 is successfully attained by TELE-EDesC with rubrics group.

The sub-competency SOP4 is that "students should be able to write structured design statement". SOP4 is thus a key sub-competency and essential to develop the overall Structure Open Problem competency. SOP4 sub-competency expects system level thinking amongst students and requires integration of a variety of concepts together (Frank, 2002). System level thinking expects students to decide and execute different decisions, and think about the sequence of decisions (Davidz, & Nightingale, 2008). It seems rubrics is helping students to develop system thinking by providing them guidance about the tasks in the system and the way to attain these tasks through criteria based descriptive scale.

This is further supported by the students' feedback taken in the form of focused interview questions. In the feedback session students were directly asked about their opinion about the self-assessment rubrics in TELE-EDesC. Some of the quotes from students' feedback are given below:

"If I know where I go wrong and I also know how I should correct myself I can design the system. Rubrics showed me where to reach to attain high score"

"Assessment rubrics gave me correct answers and also it gave me sequence of questions"

"After I read the assessment rubrics I again studied the material given to me and selected answers for questions and read feedback which told me how to select answers"

Most of the students who interacted with researcher they appreciated rubrics as it guided them how to interact with the learning material. The addition of self-assessment rubrics guided students towards successful design. Self-assessment rubrics guides students by making the design thinking process visible through their current level of achievement of the corresponding sub-competency (rubrics score), constructive feedback and expected criteria of rubrics to attain the competency. This further helped students to interact with Learning Dialogs in productive manner which reflected into improved scores of all sub-competencies. While the effect of the self-assessment rubrics could not be captured in the difference in rubrics scores, the SAT diagram and students' perceptions indicated that the self-assessment rubrics added additional learning benefit to the existing TELE-EDesC in guiding students through the process of design.

7.4. Transfer of competency to new topic

The main objective of TELE-EDesC is to help student to attain design competencies which are measurable outcomes for engineering design thinking skill. Thinking skills are defined as sense making cognitive processes (Beyer, 1988) and are transferrable to new context. We are trying to develop engineering design thinking skills, one of the important goals is that students should be able to apply the design thinking skill to new contexts. Hence, after showing that students who learn with TELE-EDesC are able to solve problems in similar topics, we now examine if students are able to apply the learnt thinking skill to a new topic. In Chapter 6, we showed that students are able to apply Structure Open Problem (SOP) design competency to the problems based on topic of TELE-EDesC. The next step was to test transferability of skill to new topic. With the addition of the self-assessment rubrics in the revised version of TELE-EDesC, we are also interested to investigate the role of self-assessment rubrics in transfer of sub-competencies to new topic.

Traditionally, transfer has been considered as an independent application of knowledge and skills acquired in one situation into another (Bransford and Schwartz, 1999). This approach, termed as ‘Direct Application’ has been criticized because of its narrow criteria for successful transfer measured by performance on sequestered problem solving (Corte, 2003), as well for its view of knowledge as a static entity (Hatano and Greeno, 1999). A more current approach to understanding transfer is ‘Preparation for Future Learning’ (Bransford and Schwartz, 1999) which is a broader approach focusing on students’ abilities to learn in new contexts. The new context is not isolated, and can involve supports that help the learner perform the task in the new situation. This approach considers learning to be active and constructive. In the ‘Preparation for future learning’ approach, metacognitive skills play an important role. To promote transfer, teaching-learning environments need to support constructive learning processes, enhance students’ self-regulation, and should encourage students to use their knowledge and skills productively and consciously (Corte, 2003).

TELE-EDesC effectiveness study indicated that students can acquire sub-competencies and Learning Dialog work as metacognitive coach to acquire these competencies. The next study was conducted to test transferability of acquired competency to new topic from analog electronics domain. This study was conducted with the objective of finding the role of self-assessment rubrics in transfer of competence.

RQ3.2.What is the role of self-assessment rubrics in transfer of sub-competencies to new context?

7.4.1. Methodology

Two groups post-test only controlled experiment was conducted to find transferability of SOP design skills to new topic. We continued with same group of students from previous experiment. The second step was transfer test. Both groups were given material in the topic of DC circuit design. Students had learnt the theoretical concepts in this topic in a prior course, but they were not familiar with design of circuits in this topic. The new learning material was in the form presentation slides with diagrams and explanation of decision steps. Students studied the material for 30 min. They were given a paper & pencil 'Transfer' test in which they had to structure an open problem in the new topic, DC circuits.

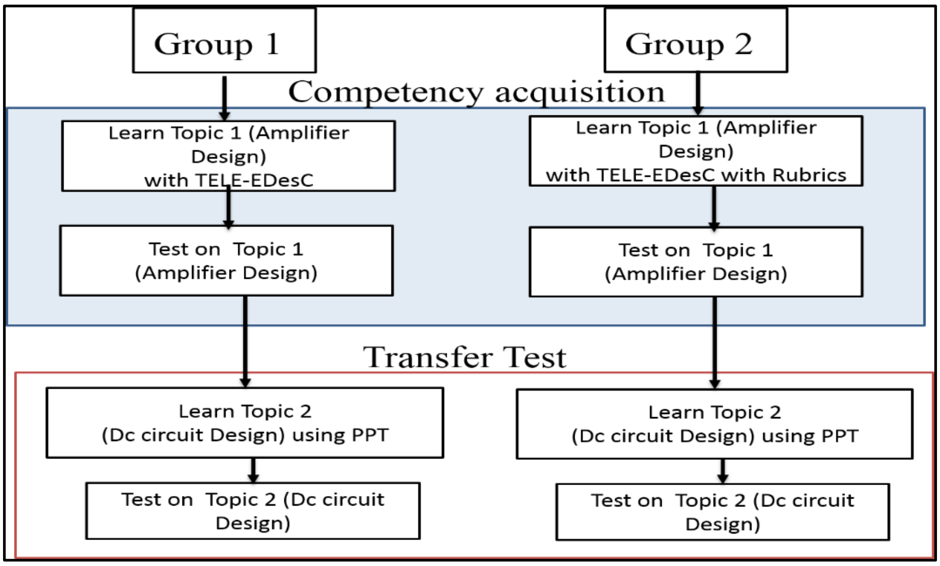


Fig. 7.3. Procedure for transfer of SOP competency in new context

7.4.2. Data analysis and results

To assess students' ability to transfer Structure Open Problem competencies, we used assessment rubrics. As mentioned in previous chapters rubrics were valid and reliable. Students' written solutions to the problem were coded using descriptive scale of rubrics. Data analysis was carried out in three ways as follows:

1. Rubrics mean scores of 'Competence Acquisition test' and 'Transfer test' for control group who learned using only TELE-EDesC Learning Dialogs are tabulated.
2. Rubrics scores of 'Competence Acquisition test' and 'Transfer test' for experimental group who learned using only TELE-EDesC + Rubrics Learning Dialogs are tabulated.
3. Finally we compared 'Transfer test' scores of experimental and control group.

1. Mean scores within control group:

Rubrics scores are ordinal data, the medians for the two tasks are calculated and table 7.3 shows mean scores and medians for two tests in control group.

Table 7.3. Mean scores for competency acquisition test and transfer test in control group

Sub-competencies	Test	Mean Scores
SOP1	Competence Acquisition	2.5
	Transfer Test	2.3
SOP2	Competence Acquisition	2.2
	Transfer Test	2.0
SOP3	Competence Acquisition	2.4
	Transfer Test	1.8
SOP4	Competence Acquisition	2.3
	Transfer Test	1.4

In control group, students transfer test score in new topic are almost same as that of competency test in SOP1 & SOP2– i.e. they were able to transfer the competencies. For SOP3,SOP4 transfer score is reduced.

2. *Mean scores within experimental group:*

We calculated mean scores for 'Competence Acquisition test' and 'Transfer test' in experimental group (Table 7.4).

Table 7.4. Mean scores for competency acquisition test and transfer test in experimental group

Sub-competencies	Test	Mean Scores
SOP1	Competence Acquisition	2.7
	Transfer Test	2.6
SOP2	Competence Acquisition	2.5
	Transfer Test	2.5
SOP3	Competence Acquisition	2.6
	Transfer Test	2.4
SOP4	Competence Acquisition	2.4
	Transfer Test	2.0

In experimental group, the scores are similar for SOP 1, 2 & 3 but SOP4 reduced slightly.

3. *Comparison of transfer test scores between experimental and control group:*

We calculated mean scores and mean ranks of transfer test scores for experimental and control group as shown in Table 7.5. The mean scores and mean ranks of experimental group students are higher than that of control group students on all sub-competencies. We conducted Mann-Whitney test to evaluate if the difference was statistically significant. Table 7.5 shows results of statistical test.

Table 7.5. Mean scores and ranks of transfer test scores of control and experimental group.

Sub-competencies	Group	Transfer test mean	Mean ranks	Z score	p-value
SOP1	Control	2.3	20.84	1.14	0.25
	Experimental	2.6	24.30		
SOP2	Control	2	19.65	1.74	0.08
	Experimental	2.5	25.61		
SOP3	Control	1.8	19.19	2.02	0.04
	Experimental	2.4	26.11		
SOP4	Control	1.4	18.89	2.11	0.03
	Experimental	2.04	26.45		

There was statistically significant difference between mean ranks of SOP3 ($0.04<0.05$) and SOP4 ($0.03<0.05$), but no statistically significant difference found in SOP1 ($0.25>0.05$) and SOP2 ($0.08>0.05$). This indicated that TELE-EDesC Learning Dialogs are sufficient to acquire and apply metacognitive processes required for SOP1 and SOP2. On the other hand, self-assessment rubrics are necessary to acquire and transfer metacognitive processes required for SOP3 and SOP4.

Self-assessment rubrics overall provides students with reflection cues and train students not only for application of knowledge, but process as well. This is reflected in the scores of experimental group on transfer test. Students who studied using TELE-EDesC with self-assessment rubrics are able to transfer all sub-competencies including SOP4. The self-assessment rubrics work as a metacognitive coach in such a way that students are trained for system thinking which involves deciding smaller components, connecting these components, thinking of interaction of these components etc. Finally Learning Dialogs like DMTQ (Decision making question), CCQ (Concept Clarification Questions), and Simulative Manipulation (SM), Controlled Animation (CANM) and self-assessment rubrics as metacognitive coach are recommended to teach SOP design competency.

7.5. Summary

The sub-competency of writing structured problem statement from open problem requires students to perform synthesis operation by integrating various decisions and concepts. Attainment of this sub-competency leads to the overall goal of structuring of open problem, which is a key step in the engineering design process. The self-assessment rubrics trigger the process of synthesis by providing students metacognitive scaffolds in the form of the description of the target performance as well as lower levels of performance. These scaffolds make the key steps in the design thinking process visible for students. They prompt students to carry out formative assessment of their performance, monitor and revise their achievement level and plan their learning based on target level.

Design tasks are open ended and the development of design thinking involves complex cognitive processes. The TELE-EDesC Learning Dialogs such as Decision Making Task Questions, Concept Clarification Questions, and Simulative Manipulation trigger students to perform the metacognitive processes involved in design thinking. Self-assessment rubrics provide students the opportunity for thoughtful reflection and improvement of their work in these activities. The rubrics help simplify the complex design tasks by providing transparent criteria of evaluation to students. This might have helped students to apply the engineering design competencies learnt in TELE-EDesC to new problems.

In Chapter 8, we try to expand boundaries of our solution along three dimensions, viz. content, design problem level and design competency. We describe the possibility to develop TELE-EDesC modules for topics other than analog electronics circuit domain. We test applicability of TELE-EDesC to develop SOP competency among students to solve higher level design problems. We also applied the pedagogical framework developed in Chapter 5 to design TELE-EDesC learning modules for other design competencies.

Chapter 8

Extension of TELE-EDesC

Chapters 4 and 5 answered the research question of "How to develop and assess engineering design competencies?" Assessment rubrics (Chapter 4) are our solution to assess engineering design competencies and TELE-EDesC (Chapter 5) is the solution to develop engineering design competencies. Chapters 6 & 7 addressed the effectiveness of the TELE-EDesC to develop Structure Open Problem competency. Originally (Chapter 1), we defined the scope of TELE-EDesC in terms of content, design competency and type of design problem. Our focus in terms of content so far has been analog electronics circuit domain, and the design competency for development of TELE-EDesC modules is 'Structure Open Problem' (SOP) design competency. The type of design problems targeted in TELE-EDesC are 'Innovative design problems, (Brown & Chandrasekaran, 1989). In this chapter we present the possibility to extend the scope of our solution. The following are three directions in which we try to extend the boundaries of our solution:

1. Development of TELE-EDesC modules for domains beyond analog electronics circuits.

The major modules of TELE-EDesC are based on topics from analog electronics circuit design. In Chapter 5 we developed specific guidelines to prepare content and for writing Learning Dialogs and created a template based on the guidelines. The template thus works as a tool to help teachers who wish to design content in their domain. In this chapter, we describe the usage of the template by two teachers who designed TELE-EDesC modules for their respective domains - Antenna design (which has some similarity with analog electronics circuits), and design of scheduling algorithm in computer science.

2. Application of pedagogical framework (Section 5.5) to design competencies other than SOP.

In the process of development of TELE-EDesC, a pedagogical framework emerged to design the learning modules. This framework provides the steps to identify and design Learning Dialogs, starting from learning outcomes of engineering design competencies. As an intermediate step, it identifies the underlying metacognitive processes necessary to develop various competencies. This framework was applied to identify and design Learning Dialogs of SOP design competency (Chapter 5) and empirically tested (Chapters 6 & 7). In this chapter we apply this framework to other design competencies. We identify Learning Dialogs for Multiple Representation (MR) design competency, and the underlying metacognitive processes for Divergent Thinking (DIV), Convergent Thinking (CONV) and Information Gathering (IG).

3. Application of TELE-EDesC modules to develop SOP competency for creative level design problems (Brown & Chandrasekaran, 1989).

We showed in Chapters 6 & 7 that students were able to attain SOP design competencies while solving innovative design problems. We expect that students trained to use TELE-EDesC develop metacognitive processes to attain SOP competency. We now extend this to test if students who learn with TELE-EDesC can apply the acquired SOP competency to higher (creative) level design problems. Students worked with six existing TELE-EDesC modules (3 topics) for 5 weeks. They were then tested for SOP competency to structure a creative level design problem.

8.1. Development of TELE-EDesC modules for SOP in new domains

In this section, we describe the development of TELE-EDesC for the content in topics beyond analog electronics. In order to develop content for other topics we developed a template (Section 5.5.1, Appendix III). The template provides guidelines to select appropriate topics from the domain in order to develop Learning Dialogs for SOP competency. In this study, two teachers applied the template to design TELE-EDesC modules for topics from their domain. We describe the examples designed by teachers using the template. We also describe our evaluation of the content, problem selection, learning objectives and Learning Dialogs from the examples in the new topics.

8.1.1. Development of TELE-EDesC modules

In order to develop TELE-EDesC for SOP competency, teachers applied the template (Appendix III) to the topics from their domain. Two teachers from respective domains of microwave circuits and computer programming developed TELE-EDesC modules for topic of micro strip antenna design for wireless applications and design of scheduling algorithm respectively.

The first part of the template guides the user to prepare content for modules and the second part provides guidelines for creating Learning Dialogs (Section 5.5).

Table 8.1. Steps and guidelines applied by teachers in content preparation phase

Steps	**Guidelines for user**	**Example1 (Microwave antenna design)**	**Example2 (Computer programming)**
Instructional topic is selected which includes design problems.	Select Instructional topic from book chapter or from module of the course.	Microwave antenna designs for different applications	Process scheduling in operating system
Open design problem is selected from chosen instructional topic	Select open design problem. In open design problem all design requirements or goals are not explicitly mentioned in the problem statement and student needs to extract relevant information from problem and decide design goals. Open design problem has multiple solutions.	WLAN is established in the office building and you are designing antenna to pick up signal faithfully and efficiently. Write design plan for this application	Write a program to choose the best scheduling policy given the list of processes.
Complete solution is written for the selected problem.	Write complete solution. Solution must contain all steps and reasoning for each decision step.	Decide the dielectric to be used. Assumed constants such as εr, h ,tanδ . Decide the frequency of operation.(Application) Decide the shape of the patch. Decide the mode of operation. Apply proper formulae. Find dimensions of patch and feed location.	Given the processes CPU burst times, arrival times , Priority and time quantum calculate the average waiting time and average turnaround time for FCFS, SJF, Priority and Round robin for each process Calculate average waiting time and turnaround time for each process scheduling algorithm Compare the average waiting time and turnaround time , the process scheduling algorithm with the least time will be the most appropriate scheduling algorithm.

In the content preparation phase, the open design problem from the topic is chosen and its solution is written. Further, the content is divided into small modules depending on the concepts involved. In order to prepare content it is expected that user should be able to select appropriate open design problem as per given guidelines. Open design problem belongs to innovative category in which specifications are partially available. Table 8.1 shows steps applied by teachers in content preparation phase. The examples in table 8.1 are written by the two teachers who participated in the study.

In the case of microwave design the WLAN application is provided which demands for design of micro strip antenna which is hidden specifications of the problem. In this design main concept was related to impedance matching and adjustment of frequency tuning circuits to ensure maximum reception of signal. Selection of passive components is an important aspect of antenna design. In computer scheduling design user need to decide criteria to select best scheduling policy which makes the problem as open design problem.

The second part of template provides guidelines for writing learning objectives and corresponding Learning Dialogs. Fig. 8.1 shows the steps applied by teachers to write learning objectives. Fig. 8.2 shows steps to design Learning Dialogs for learning objectives.

Guidelines for writing Learning Objectives—

Write learning objectives .

1) *What is learning objective(LO)?*

(LO is specific, measurable performance outcome of student.)

2)How to write LO?

Each step from solution analysis is used to write learning objective. Step of solution:-

1.Student should be able to identify and interpret relevant specifications/design goals/design requirements from given open problem.

Example of Learning Objective written by teacher

- *Solution step1--*
- *To find Length and Breadth of patch. Use of correct sequence of formulae.*
- *To Find approximate feed location.*
- *Learning Objectives*
- *Student should be able to apply appropriate formula to find length and breadth of patch.*
- *Student will able to calculate feed location for antenna design*

Fig. 8.1.Writing learning objectives using template

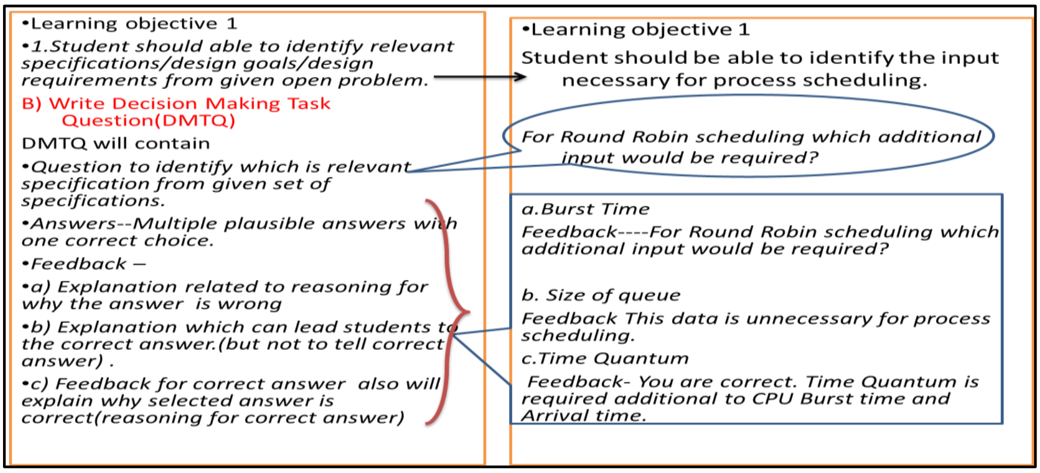


Fig. 8.2. Learning Dialogs for topic of scheduling developed using template

The modules designed by teachers are evaluated for checking application of template in appropriate manner i.e. whether learning objectives and Learning Dialogs are aligned with the instructions of template. In next few paragraphs we described the criteria of evaluation of these modules. The first two criteria are related to content preparation phase in which teachers selected topic and open design problem.

Criteria –Problem selected is open problem. Problem selected has multiple solutions; multiple ways to attempt problem and specifications, decision etc. are to be fixed up by designer.

Evaluation.

Example 1. In the topic of micro strip antenna design which is similar to topics from analog circuit design, it was found that multiple types of antennas can be designed for given application. Designer need to select range of frequencies and accordingly tuning circuits will be designed. Designer need to decide how much power is to be delivered. Thus problem selected has multiple solutions and designer will take decisions at various steps, decide specifications based on availability and application. So the problem selected for design of module satisfies the definition of open design problem.

Example 2. In the topic of computer programming design of scheduling algorithm is selected. For a given situation different types of algorithm are possible. Designer need to select list of processes and decision of selecting algorithm is taken by designer. This also satisfies the definition of open design problem.

Criteria: Learning objectives are properly written. Learning objectives contain measurable sub-competencies. The content of LO aligned with the problem solution.

Evaluation.

In both examples, learning objectives are written based on measurable sub-competency and it is aligned with the definition of LO. Appropriate actions verbs are applied to address expected cognitive level.

Criteria: Learning Dialog of DMTQ is written correctly. DMTQ appears at decision making step. The question triggers relevant decision making process. Answers of DMTQ are plausible and feedback for each answer is directional explanatory one.

Evaluation.

Example 1. For Antenna design DMTQ is developed at method selection decision step and question is “Which of the following feeding method can be used for better performance of the antenna?” The answers provided are plausible answers and for each answer pros and cons analysis is explained. Thus this question satisfies all requirements of DMTQ.

Example 2. For topic of scheduling algorithm design the question asked at decision making step was: “For Round Robin scheduling which additional input would be required?” Multiple plausible answers are given, but feedback for each answer is explanation but not directional or supportive to take decisions. This activity thus does not represent true DMTQ and feedback need to be provided elaborately. This may point to the training to be given to faculty for writing Learning Dialogs.

Criteria: Learning Dialog of Controlled Animation is written correctly. Controlled Animation is designed for representing specifications which need Multiple Representation for interpretation. Proper representation need to be identified and relation between two representations should show with slow speed as well as possibility to control the animation.

Evaluation.

Example 1. In antenna design, animation is shown for selecting dielectric material depending on dielectric constant. But as per definition animation need to be designed to explain the specification while in this case animation is used for decision making. Thus there is misalignment with the purpose of dialog.

Example 2. For scheduling algorithm design specification of burst time of CPU is explained using graph. This matched with the requirement of animation.

Criteria: Learning Dialog of Simulative Manipulation (SM) is written correctly. SM requires showing relation between two variables for purpose of experimentation. Question followed in SM should lead to decision thinking process.

Evaluation.

Example 1. In antenna design topic the content suitable for SM is mentioned by teacher, but actual Learning Dialog with appropriate diagrams are not drawn. Selected content is appropriate as it shows relation between two variables which need to be used for experimentation purpose. For the topic of scheduling, content for SM is identified and is appropriate as relation between two variables is required to decide scheduling process. In this module also details are not found. This activity requires careful drawing of all parameter variations and need to show corresponding changes in representation. Teachers understood the content to be designed but due to requirement of diagrams and representations they might have left it half.

The overall evaluation indicated that TELE-EDesC modules for different topics can be developed using the template. More than 70% of Learning Dialogs developed by teachers were according to the guidelines.

8.2. Application of pedagogical framework to develop TELE-EDesC for various design competencies

We apply the pedagogical framework that emerged in Chapter 5 to create Learning Dialogs for developing various engineering design competencies identified in Chapter 4. The framework starts by deciding learning outcomes for each design competency (Fig. 8.3) and identifies metacognitive processes to attain these learning outcomes. The instructional strategies to trigger these metacognitive processes are then identified using principles and strategies from learning sciences. Learning Dialogs are designed from these strategies using instructional design principles for interactive learning environment.

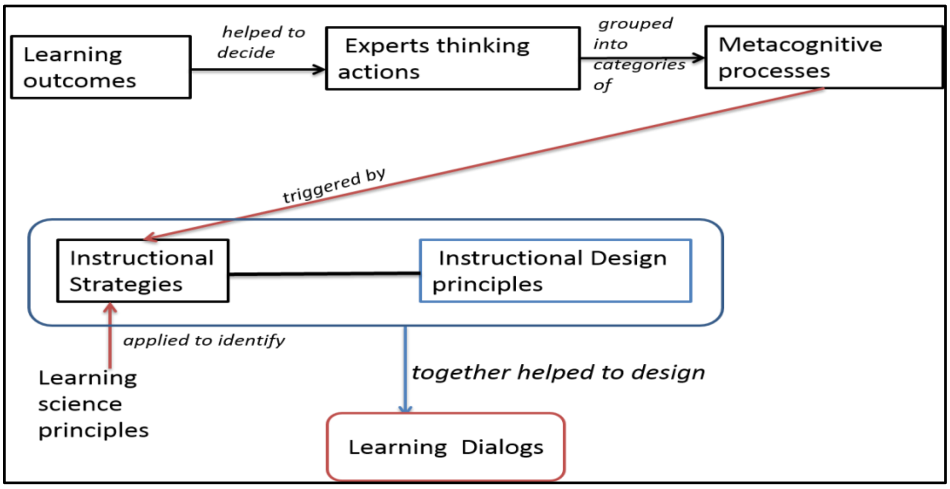


Fig. 8.3. Pedagogical framework to design TELE-EDesC (reproduced from Ch.5)

In this section we describe the detailed application of the steps in the pedagogical framework shown in Fig. 8.3 to Multiple Representation (MR) design competency. We identify Learning Dialogs of MR from the expected learning outcomes (Section 8.2.1). We also applied these steps of framework to identify metacognitive processes of design competencies like, Divergent Thinking, Convergent Thinking and Information Gathering (Section 8.2.2)

8.2.1. Pedagogical framework applied to Multiple Representation (MR)

As per the guideline steps given in Fig. 8.3 we first identified metacognitive process to develop MR, using experts' design solutions. Principles from the learning sciences are applied to decide instructional strategies to trigger metacognitive processes. These instructional strategies form the basis of Learning Dialogs of TEL environment which are designed using instructional design principles of interactive learning environment. In next few sub-sections we present a detailed application of all steps of pedagogical framework.

8.2.1.1. Analysis of experts' design solution for MR competency

Sub-competencies and target performance (Chapter 4) of MR are applied to define learning outcomes for each sub-competency (Table 8.2).

Table 8.2. Learning outcomes for sub-competencies

Sub-competency	Expected learning outcome. Students will be able to:
MR1- Construct representations for given problem.	1. Decide appropriate representations as per specifications. 2. Draw representations with all appropriate details.
MR2-Consistency of representations	1. Decide consistent representations. 2. Justify mapping between representations in all respect.
MR3-Use of representations to solve problem	1. Decide appropriate representation for problem solving. 2. Apply representations correctly to find solution. 3. Solve problem correctly using representation.

Five experts from Analog electronics circuit domain were asked to write solutions to an open design problem in amplifier design topic. Experts' solutions to these design problems were analysed to know their design thinking actions to achieve the learning outcomes. Fig. 8.4 shows the example of content analysis of an expert's design actions wise. First, all the relevant actions under sub-competencies were grouped together. Codes were assigned for each relevant action. For example, consider the design statement "*Draw a circuit of two stage BJT-FET amplifier as we need high input impedance".* This action falls under MR1 sub-competency. The code assigned to this action is 'Decide representations'. There are number of codes that emerge from the actions taken by experts to achieve learning outcomes for each sub-competency. When these codes are examined it was found that some of the actions can be categorised under common heading. For example, for "*MR1-Construction of representation"* the action of deciding appropriate representation by way of decision making using domain knowledge is required.

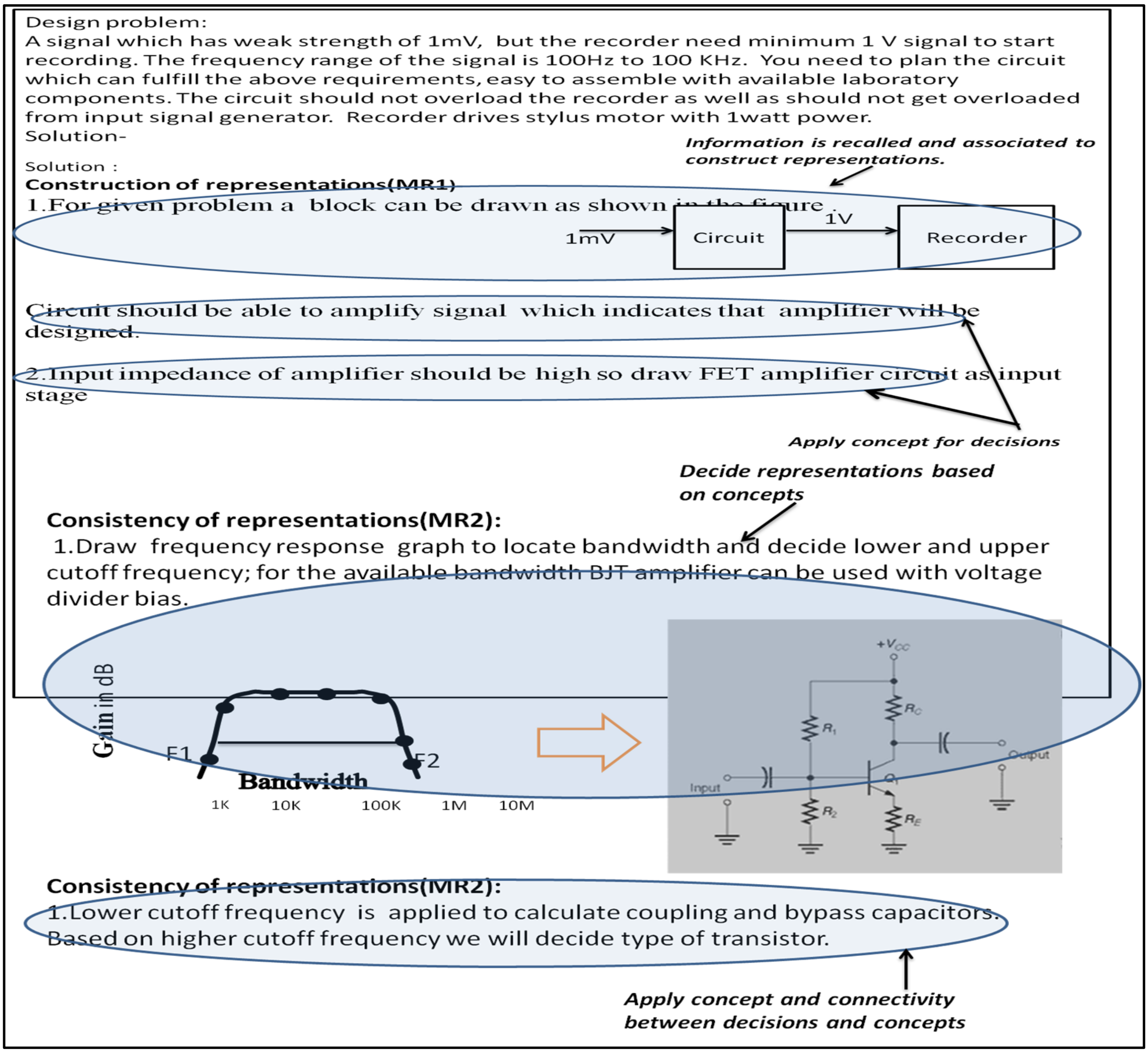


Fig. 8.4. Example of content analysis of an expert's design actions sub-competency wise.

For each sub-competency of MR such types of actions were frequently seen. Common actions were clubbed together into category. It was found that for "MR1-construct valid representation" valid representations need to be identified and then drawn correctly. In order to achieve this desired outcome decision need to be taken based on conceptual understanding. Similarly for MR2-"Consistency between two representations" link between two representations should be identified based on concepts. To establish these link students should be able to decide connection based on their conceptual understanding. Both these outcomes require decision making in different conditions. For both these competencies decision task was clubbed into decision making category. Categories emerged showed similarity with the design thinking processes identified from literature in Section 2.2, Chapter 2. These categories are found to indicate the metacognition processes (Brown & Palincsar, 1982; Biswas et.al, 2013) to be applied to attain competence in MR. Table 8.3 shows the codes that emerged for learning outcomes, and the categorisation of these codes in terms of metacognitive processes.

Table 8.3. Codes and categories for MR learning outcomes

Sub-competency	**Learning outcomes**	**Codes (experts actions)**	**Categories (metacognitive processes)**
MR1-- Construct representations--	1.Decide appropriate representations as per specifications appropriate details	Apply concepts for decision making	Decision Making
	Draw representations with all	Information is recalled and associated to construct representations.	Construction of representation
MR2- Consistency of representations	Justify mapping between representations in all respect.	Justify representation based on conceptual understanding	Complementary thinking
	Decide consistent representations.	Decide representations based on concepts	Decision making
		Decide representations based on information	Decision making
MR3-Use of representations to solve problem	Decide appropriate representation for problem solving.	Apply concepts to select part of representation	Concept Integration
	Apply representations correctly to find solution.	Apply concept and connectivity between decisions and concepts	Complementary thinking
	Solve problem correctly using representation.	Calculate values using representations.	Concept Integration

The main metacognitive processes identified from experts' design solutions to attain MR competency are decision making, concept integration, and construction of representation and complementary thinking. Our goal is that the learning activities in TELE-EDesC modules should be able to trigger these metacognitive processes by incorporating appropriate instructional strategies (Zimmerman, 2007; Ge & Land, 2004; Linn et.al, 2003). In the next section (8.2.1.2), we review research to find the recommended strategies for each metacognitive process identified in this section.

8.2.1.2. Instructional strategies for triggering metacognitive processes

Decision making involves an iterative series of divergent-convergent thinking in which students need to generate many options based on the set of information available, evaluate them based on domain knowledge expertise (Gresch, 2012). Concept integration process expects learner to select appropriate pieces of information based on domain knowledge (Chen et.al, 2011). Complementary thinking metacognition process (Ainsworth, 2006) expects learners to create referential connections between the corresponding elements to construct coherent knowledge structures (Seufert, 2003). For example in circuit problems students should be able to create connections between the components values and waveform parameters which will help them to understand function of circuits or application of given circuit. Drawing of consistent construction metacognitive process expects learners to select correct elements, arrange these elements or connect these elements to make meaningful constructions (Zacks & Tversky, 1999).

Decision making can be triggered using series of deep reasoning questions (Aurisicchio et al., 2007) as well as providing options for selection. Decision making process can be triggered using formative assessment in which series of deep reasoning questions were developed at decision step and feedback provided to guide learner for self-monitoring to aid decision process (Mavinkurve & Murthy, 2014). Concept integration is triggered by providing guided experimentation opportunity to learners (Mavinkurve &Murthy, 2014). Dyna-linked multiple representations (concurrent changes over time) with guided questions help learner to make connections between two representation (Van der Meij and de Jong, 2006) to develop complementary thinking process. Learner generated drawing (Van Meter & Garner, 2005) is recommended strategy for helping learners to construct representations. In this strategy learners are provided with key elements of constructions and guided questions are provided to connect the key elements for developing appropriate constructions.

Table 8.4 shows the instructional strategies identified to trigger the essential metacognitive processes of Multiple Representation (MR) competency.

Table 8.4. Instructional strategies for metacognitive processes

Metacognitive processes	Learning science principles	Instructional strategies
Decision Making	Planning ,monitoring and evaluation	Formative assessment question
	Self- regulation	Feedback
Concept Integration	Knowledge integration	Guided experimentation
	Information association	
Complementary thinking	Dyna-linked representations	Interpret Multiple Representations
Construction of representation	Generative theory of drawing constructions	Learner generated constructions with guidance

It was found that formative assessment questions, feedback, guided experimentation are similar to strategies suggested for SOP design competency in Chapter 5. In addition we found strategies such as learner generated constructions with guidance and interpretation of Multiple Representations.

8.2.1.3. Design of Learning Dialogs MR competency

We designed Learning Dialogs for attainment of MR based on strategies suggested in previous section 8.2.1.2. We applied Instructional Design principles like guided activity, feedback, reflection, pacing and pre-training (Mayer 2009, 2005a) to design Learning Dialogs. Some of the instructional strategies suggested for MR are similar to SOP design competency. We thus designed Learning Dialogs similar to SOP design competency mentioned in chapter 5. Decision making metacognitive process is triggered using formative assessment question. We propose Learning Dialog of "Decision Making Task Question (DMTQ)"using guided activity principle (Mayer, 2004; de Jong, 2005). This will be similar to DMTQ designed for SOP design competency.

Concept integration metacognitive process is triggered using guided experimentation strategy as suggested in Chapter 5. We propose Learning Dialog of "Simulative Manipulation" using guided activity principle (Mayer, 2004; de Jong, 2005). This Learning Dialog is also similar to one which is developed for SOP design competency. In addition to these to metacognitive processes we need to trigger process of complementary thinking and construction of representation to attain MR. For complementary thinking, recommended strategy is to help students to interpret Multiple Representations. Dynamically linked Multiple Representations are basis of this strategy. We thus propose "Simulative Manipulation" as Learning Dialog which is based on guided activity and feedback principles of Instructional Design. In "Simulative Manipulation" we propose dynamically linked MR followed by guiding questions. For metacognitive process of construction of representation, we proposed strategy of learner generated constructions with guidance. We will develop Learning Dialogs using pre-training principles. We will refer this dialog as "guided constructor" in which we will provide tool box and user will be guided to construct diagrams. At each step conceptual question with feedback will be provided to guide learner in construction process.

Table 8.5 summarizes the process of design of TELE-EDesC. It shows the mapping between metacognitive processes needed to attain MR design competency, instructional strategies that trigger these metacognitive processes, and the use of instructional design principles to design Learning Dialogs in TELE-EDesC: Decision Making Task Questions (DMTQ), Simulative Manipulation (SM), Guided Constructor, simultaneous multiple representations and Self-assessment Rubrics.

Table 8.5. TELE-EDesC Learning Dialogs for metacognitive processes of MR

Metacognitive processes	**Theoretical basis**		**Instructional Design Principles**	**Learning Dialogs of TELE-EDesC**
	Learning science principles	**Instructional strategies**		
Decision Making	Planning ,monitoring and evaluation	Formative assessment question	Guided activity and feedback	Decision Making Task Question(DMTQ)
	Self- regulation	Feedback		
Concept Integration	Knowledge integration	Guided experimentation	Guided activity and feedback	Simulative Manipulation
	Information association			
Complementary thinking	Dyna-linked representations	Interpret Multiple Representations	Pre-training Guided activity	Simulative Manipulation
Construction of representation	Generative theory of drawing constructions	Learner generated constructions with guidance	Pre-training and guided activity	Guided Constructor

Table 8.6 summarizes the entire framework to develop TELE-EDesC for Multiple Representation (MR) design competency. It combines and displays together the steps already shown in Tables 8.3, 8.4 and 8.5.

Table 8.6. Framework applied for "Multiple Representations (MR)"design competency

Learning outcomes	Expert design actions	Metacognitive processes	Theoretical Basis		Instructional Design principles (to operationalize strategy to TEL environments)	Learning Dialogs
			Learning science principles	Instructional Strategies		
MR1-Construct representations- 1.Decide appropriate representations as per specifications	Apply concepts for decision making	Decision Making	Planning, monitoring and evaluation Self-regulations	Formative assessment question and feedback	Guided activity	DMTQ
Draw representations with all appropriate details	Information is recalled and associated to represent graphs.	Construction of representation	Generative theory of drawing constructions	Learner generated constructions with guidance	Pre-training and guided activity	Guided Constructor
MR2-Justify consistency of representation	Justify representation based on conceptual understanding	Complementary thinking	Dyna-linked representations	Interpret Multiple Representations	Pre-training Guided activity	Simulative Manipulation
MR2- Decide consistent representations.	Decide representations based on concepts	Decision making	Planning, monitoring and evaluation Self-regulations	Formative assessment question and feedback	Guided activity	DMTQ
MR3- Decide appropriate representation for problem solving	Decide representations based on information	Decision making	Planning, monitoring and evaluation Self-regulations	Formative assessment question and feedback	Guided activity	DMTQ
MR3- Apply representations correctly to find solution.	Apply concepts to select part of representation	Concept Integration	Knowledge integration and information association	Guided experimentation	Guided activity and feedback	Simulative Manipulation

8.2.1.4. Evaluation of Learning Dialogs MR competency

Learning Dialogs recommended by pedagogical framework are designed using topic from analog electronics. We selected concept of BJT operating regions and its application as switch. Fig. 8.5 shows an example of a DMTQ learning dialog which directs user to decide the relevant representation for given problem.

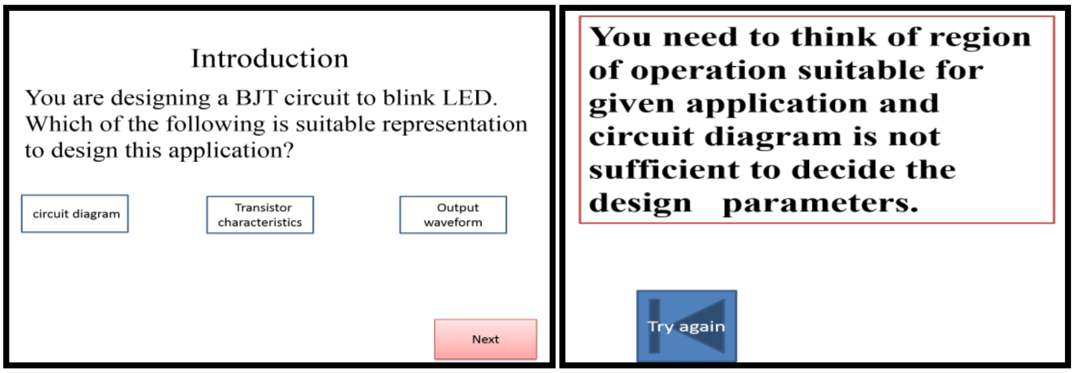


Fig.8.5. DMTQ learning dialog for Multiple Representation

Guided constructor activity contains the tool box of key elements such as load line, saturation region, cut-off region as shown in fig 8.6. Guided questions are provided to help learner to use these key elements to draw constructions and mark relevant labels of construction.

Fig 8.7 represents simulative manipulation learning activity in which we showed two representations such as circuit diagram and load line characteristics. When learner will vary values of resistor (RB) he/she will be able to see changes in load line characteristics and switching conditions of LED.

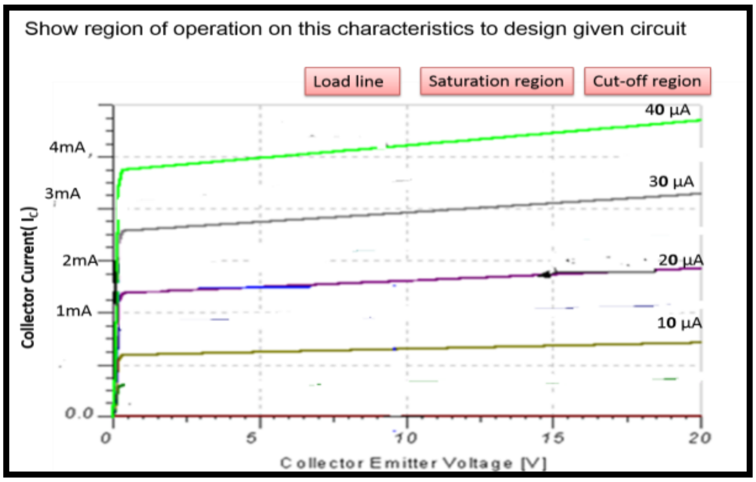


Fig 8.6. Guided Constructor

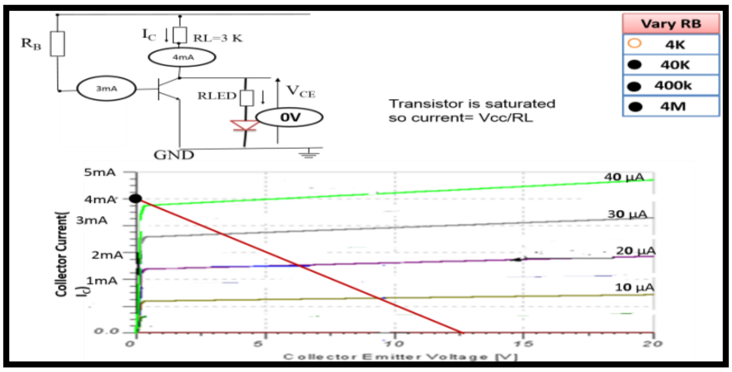


Fig.8.7.Simulative Manipulation

Testing effectiveness of learning dialog

We conducted a two group post-test quasi-experiment to test the effectiveness of the Learning activities developed for MR thinking skill.

Participants: Our sample consisted of students from 2nd year Electronics engineering (N=53). Students had some familiarity with the content in the visualization, as they had learnt it in the theory course on the same topic. They were also familiar with using ICT materials.

Procedure: Students were randomly assigned to two groups. The experimental group consisted of 27 participants and the control group had 26 participants. The equivalence between the two groups was tested on basis of their previous semester's grades and no significant difference was found between them (t=0.14, p=0.44). Two sets instructional materials on the same topic were developed. This experiment is conducted in teacher driven mode i.e. teacher used learning material to teach the topic of BJT application as switch. For experimental group teacher used TEL based instructional material to explain concept of transistor switching. Instructor showed DMTQ and asked students to write their answers and then showed feedback for each selected answer. In control group PPT slides with same diagrams, concepts are applied. But students were not given questions instead instructor explained them which is correct representation why is it a appropriate representation etc. Students in both groups were taught by same teacher for 30 minutes, after which they attempted the post-test. The test was based on application of transistor as switch but the application was for development of digital test signal was given in post-test.

Instrument: To assess the development of students' multiple representation competency (and sub-competencies) we used assessment rubrics, which had a 4-point scale: 0-Missing, 1- Inadequate, 2-Reasonable but needs improvement, 3-Good. Each rubric item corresponded to one sub-competency (MR 1-3).For e.g. In order to assess MR1 the target performance level was described as constructions are valid as per problem requirement and all primary and secondary details are present in the constructions. These rubrics were validated prior to the experiment. Inter-rater reliability testing was found to give 94% agreement between 3 instructors.

Results

The scores on the post-test are ordinal data; hence we used a Mann-Whitney U-test for analysis. The mean ranks for each sub-competency for the two groups are shown in Table 8.7. The results show that the mean ranks for the experimental group are significantly ($p<0.001$) higher in each sub-competency. We inferred that learning activities proposed in our study helped learner to develop MR competency for topic of BJT application

Table 8.7: Comparison of experimental group and control group MR sub-competency scores

Sub competency	**Group**	**N**	**Mean score**	**Mean Rank**	**z**	**p**
MR1	Control	26	0.88	17.04		
	Expt	27	1.85	36.59	4.59	<0.01
MR2	Control	26	0.26	16.52		<0.01
	Expt	27	1.51	37.09	4.83	
MR3	Control	26	0.26	17.79		<0.01
	Expt	27	1.25	35.87	4.25	

The results confirmed that the learning dialogs suggested by pedagogogical framework developed MR thinking skill and framework is applicable for identifying learning dialogs to develop other design competencies than SOP(structure open problem).

8.2.2. Identification of metacognitive function for other design competencies

The pedagogical framework developed in Chapter 5 is also partially applied to Information Gathering, Divergent and Convergent thinking design competencies and metacognitive processes are identified using the same process described in 8.2.1.1 (Table 8.6). This further will help researchers to develop Learning Dialogs for these competencies.

Table 8.8. Metacognitive processes for Information Gathering competency

Competency	**Sub-competency**	**Learning outcomes**	**Expert design thinking actions**	**Metacognitive Processes**
Information Gathering	IG1	List all information sources required for design.	Use concepts to select sources.	Concept Integration
		Justify relevance of selected sources for design	Decide relevant sources using concepts	Decision making
	IG2	Write relevant information useful in design from selected sources.	Use concepts to write information	Concept integration
		Justify selected information.	Using conceptual understanding decide relevance of information	Decision making

Table 8.8 provides the metacognitive processes to be triggered to achieve learning outcomes for Information Gathering (IG). This established the possibility to design TELE-EDesC for other design competencies by applying steps of pedagogical framework.

Table 8.9. Metacognitive processes for Divergent thinking

Competency	Sub-competency	Learning Outcomes	Expert design thinking actions	Metacognitive processes
Divergent thinking	DIV1	Write all possible solutions.	Conceptual thinking to find different possible circuits	Knowledge application
		Explain all details of solutions	Recall information and draw circuits.	Information association
	DIV2	Identify all variations in the specifications.	Conceptual thinking is required to decide specifications. Apply specifications to analyse performance of different circuits.	Analytical processing
		Justify solutions based on specifications.	Concept applied to analyse the circuit combinations.	Concept Integration
	DIV3	Evaluate pros and cons of solutions.	Evaluation is done for each circuit based on specifications	Evaluative process
		Decide solutions based on pros-cons analysis	Converging evaluation process to decide circuit.	Decision making
	DIV4	Apply methods to solve problems	Apply knowledge and process to solve problem	Knowledge application

Table 8.9 provides the metacognitive processes to be triggered to achieve learning outcomes for design competencies like Divergent Thinking and table 8.10 for metacognitive processes of Convergent thinking design competencies.

Table 8.10. Metacognitive processes for Convergent thinking

Competency	Sub-competency	Learning Outcomes	Expert design thinking actions	Metacognitive processes
Convergent Thinking	CONV 1,2	Justify selected solution based on different aspects of design parameters	Visualise selected circuit Analyse circuit Verify the appropriateness of each selected stage Map solution with principles.	Decision mapping
	CONV 3	Select solutions based on specifications or constraints	Converging of concepts and process of analysis to decide circuit based on specifications.	Synthesis
	CONV4,5	List suitable assumption and justify them	Use information to write assumptions. Use conceptual understanding to justify assumptions.	Concept integration
	CONV6	Write complete solution	Apply information, concepts, process to write design solution.	Synthesis

8.3. TELE-EDesC to develop SOP for Creative level design problems

Engineering design problems are categorized as routine, innovative and creative (Brown, & Chandrasekaran, 1989).

In 'routine' design problems, the effective problem decomposition is known. In electronics circuit design problems, effective decomposition of problem means all specifications are known. In routine problems mapping of sub-functions into physical components is clear, that means type of circuits suitable to meet given specifications are mentioned in the problem. The only task is to select appropriate components that optimise well established criteria. This problem is solved using fixed formulae. Designer will decide appropriate formula to be used and calculate component values and select practical values. Decision making scope is limited to selection of practical components for design.

For example, "Design class –B push pull amplifier to deliver power of 2 Watt to 8 ohm load". In this problem type of power amplifier is known so students will recall the circuit. The power rating and load is given so they will calculate appropriate currents, voltages and will select components in the circuit.

In 'innovative' design problems, the top level functional decomposition is known, that is, the type of circuits to be designed, such as, amplifier, filter etc. are given. But physical realisation of sub-functions require considerably more efforts, this means designer need to extract all relevant specifications for given application and decide which type of filter or amplifier is suitable in the given application. In this type of problems real world problem is given and multiple solutions are possible. *For example "Design power amplifier to amplify audio signal for paging announcement of supermarket with speaker rating of 8 Watt".* For this type of problems specifications need to be identified by designer and multiple circuits are possible based on identified specifications. Designer need to compare these circuits based on characteristics.

Creative design problems are still more open ended. In these types of design problems, the functional specifications are open ended, effective decomposition is not known and designer need to evaluate multiple options. This problem specifications are not mentioned clearly, circuits are unknown and there is possibility of multiple circuits which can achieve these goals. Designer should be able to translate given problems into block diagrams as per expected working of the circuit.

Creative design problem solving is cognitively hard task and includes many interrelated activities such as identification of entire system as well as individual blocks of system, relevant circuits in each block, pros and cons analysis of selected circuits or blocks, identifying and analysing relevant specifications, thinking of interfacing between circuits and or blocks etc. For electronics circuit *"Design an amplifier for a rock musician who needs to perform in an open-air theatre in front of an audience of a thousand people".*

In order to structure innovative design problem students need to take decisions at various steps and even integrate different concepts. Metacognitive processes like decision making and concept integration are essential to attain SOP competency. In creative design problems, the complexity of decisions increases and students need to take multiple decisions at a time, and integrate different types of concepts and information at deeper level. But the basic metacognitive processes remain the same, what changes is its application. Thus it is expected that if students attain SOP competency by internalising these metacognitive processes they may be able to structure creative level design problems.

Students in undergraduate engineering programs face difficulty in solving design problems. They are trained in solving routine design problems, which are a part of the curriculum. Within the curriculum they are not exposed to higher level problem solving process; instead they are directly exposed to creative level problems for their final year (senior) projects. Thus students perform poorly at creative level problem solving, and even at innovative level problem solving.

TELE-EDesC is an intermediate step to train students for innovative level design problems. The TELE-EDesC modules designed as part of this thesis cover a range of topics in analog electronics circuit domain (4 topics, 8 modules). In order to expand the utility of TELE-EDesC learning modules, we trained students with these modules progressively before exposing them to a creative design problem. The next section describes a longitudinal study conducted to progressively train students to develop SOP design competency in innovative problems, and tested repeatedly. Finally, students are given a creative design problem to test if they are able to transfer SOP competency. The Research Question in this study is:

RQ.3.3. Are students able to transfer the SOP competencies to a Creative level design problem after learning from TELE-EDesC?

8.3.1. Research method

Research Design:

A longitudinal study for 5 weeks was conducted in which students worked on one TELE-EDesC module each week for the first 3 weeks (Topics – DC circuit design with Q-point location, Amplifier design, Op-Amp comparator). Longitudinal study is effective to establish causal relationship and for making reliable inferences (Ruspini, 2002). Sampling error is reduced as same sample is studied over a time period. In this study, the effect of intervention (TELE-EDesC) modules on students acquisition of SOP sub-competencies is tracked and further transfer of these sub-competencies to higher level of problems (creative design) is studied. Single group time series design with post-test only research design was applied.

Participants:

Purposive sampling is done for this study. This is a five week study with third year students and they spent time on this activity from their electronics lab time. It was difficult to disturb entire batch of students for the entire time period as well as arrange resources. Thus ten students were selected for additional learning with TELE-EDesC as part of the electronics lab. Participants were third year students (N=10, Male=6, Female=4) from course of Electronics and Communication Engineering. Since the purpose of our study was to track attainment of SOP competency, we selected participants who had demonstrated conceptual understanding based on their scores on the previous semester's test on analog electronics.

Procedure:

This is longitudinal study of five weeks in which students worked with 2 TELE-EDesC modules every week. Each TELE-EDesC modules was studied for 30 minutes. After that, students were given a test in which they had to structure a new open problem based on topics from the TELE-EDesC module. In the first week of study, students were given a creative design problem as a pre-test. The topic of this test was related to the design of a Function Generator for application to junior level science students for laboratory measurement purpose. The problem given was "*You have joined an equipment manufacturing company after graduation. You have been assigned the job of designing function generator for educational institutes. These institutes include first year science classes for junior college as well as engineering institutes. Write how you will plan your design on paper in detail with specifications, block diagram etc.*"

Student wrote the solution to this problem which were then evaluated using SOP competency assessment rubrics (Table 4.4, Chapter 4). In the following week (Week 2), students worked with two TELE-EDesC modules for topic of DC circuit design (Q point location). The fundamental concepts of amplifier design are addressed in this module. Students studied one topic for an hour, in which they studied each module of the topic for 30 minutes and then wrote a post-test in which they had to solve a semi-structured innovative level design problem on the same topic (but different problem than what they learnt in TELE-EDesC). Students were given 30 minutes to solve this problem. They were able to attempt question within the stipulated time. In consecutive weeks the same process was adopted for second (Amplifier design) and third (OP-Amp) topic. Overall students were trained with 6 modules of three topics (Fig. 8.8) in weeks 2, 3 and 4. In the last week of study (week 5), they were given the same Creative level design problem which they attempted in pre-test. Students' solutions were assessed on SOP design competencies for this design problem using rubrics.

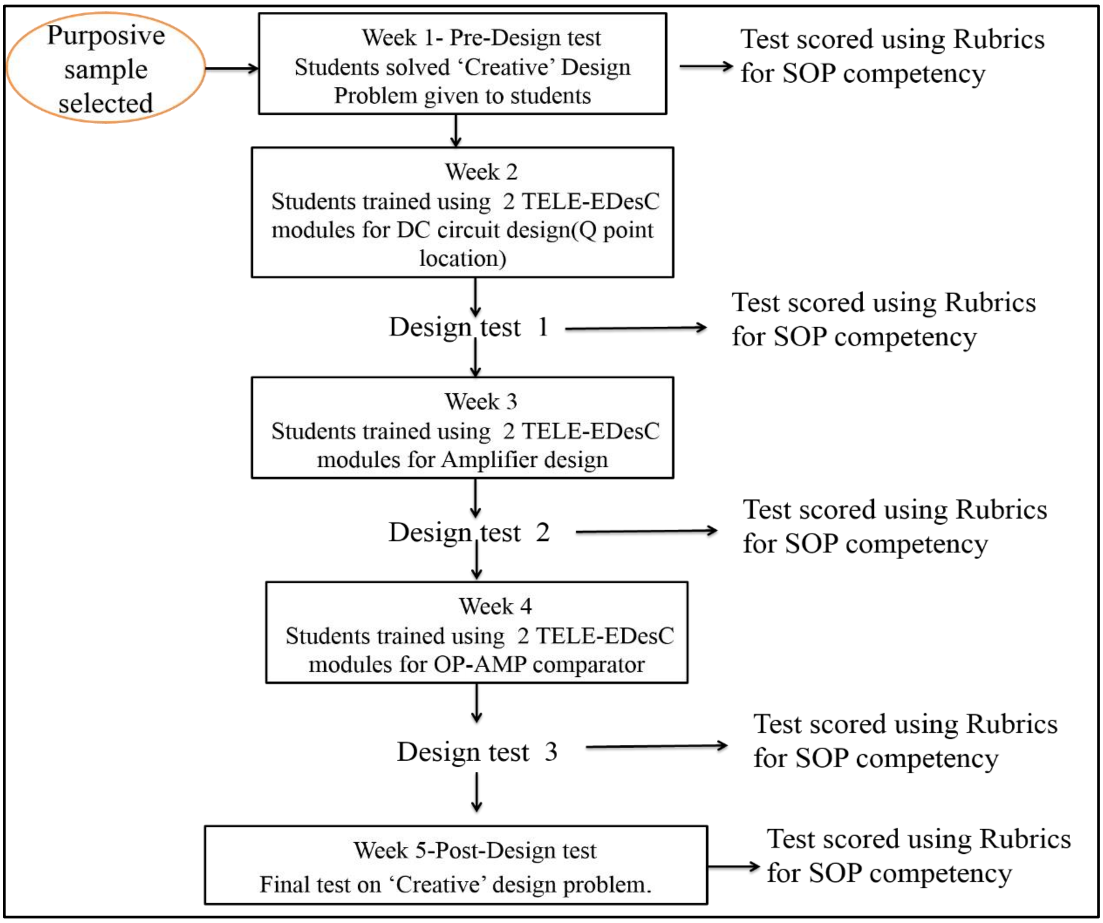


Fig. 8.8. Stages of longitudinal study

Instrument:

The rubrics developed and validated for Structure Open Problem design competency (Chapter 4) were used to assess students' post-test responses to the design problem. As described in Section 4.3, the rubrics were tested for inter-rater reliability, which was found to be kappa = 0.73 for SOP competency.

8.3.2. Results

a) Attainment of sub-competencies

Students' responses to post-test and creative design problems were assessed using rubrics. Table 8.11 shows the mean scores for each sub-competency for all modules and creative design problem. Fig. 8.9 shows the tracking of progress of sub-competency scores of students in longitudinal study.

For creative design problem, in the pre-test, scores were low for all sub-competencies. For SOP1 students scored near the target performance level, while other three sub-competencies competency level was at inadequate. Students' SOP competency scores progressively improved for all sub-competencies, as they studied using TELE-EDesC modules (Fig. 8.9).

Table 8.11. Comparison of SOP sub-competency mean scores

Treatment	**SOP1**	**SOP 2**	**SOP 3**	**SOP 4**
Creative problem (initial pre-test, before treatment)	1.57	1	1.14	0.42
TELE-EDesC (DC circuit design)-2 modules	2.42	2.28	2	1.28
TELE-EDesC (amplifier design)-2 modules	2.28	2.28	2.28	1.85
TELE-EDesC (OPAMP comparator)-2 modules	2.42	2.28	2.57	2.28
Creative problem (post-test, after training)	2.57	2	1.85	1.42

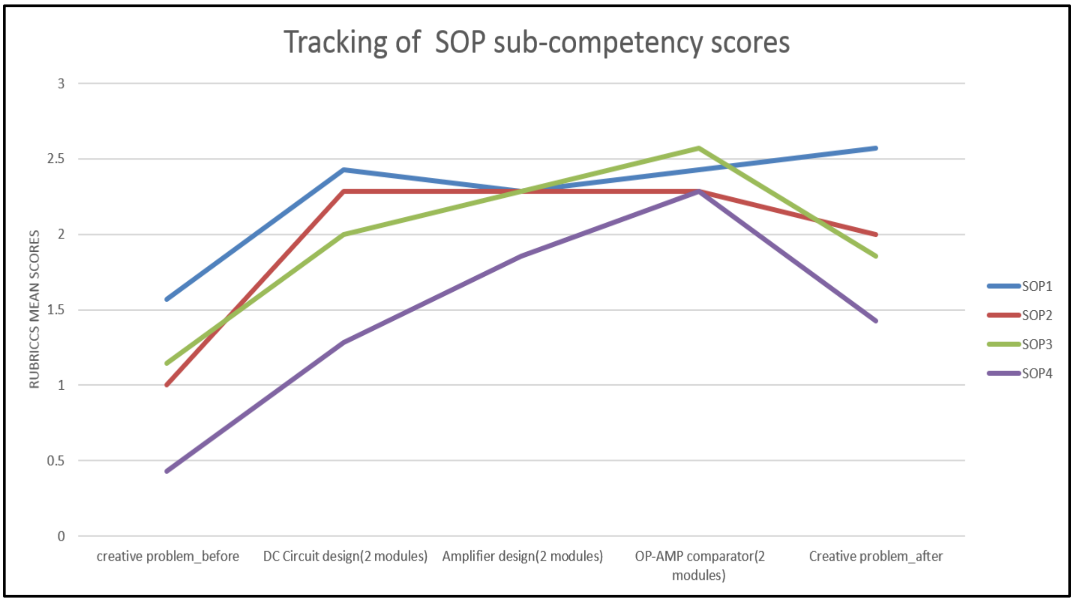


Fig. 8.9. Tracking of sub-competencies scores of students in time series experiment. The horizontal axis effectively represents time.

b) Transfer of sub-competencies to structure creative level problem

Table 8.12. Comparison of SOP sub-competency ranks for statistical significance

Sub-competencies	**Modules**	**Mean scores**	**Median**	**Z score**	**p value**
SOP1	Creative problem before	1.57	2	-2.07	0.03
	Creative problem after	2.57	3		
SOP2	Creative problem before	1	1	-2.33	0.02
	Creative problem after	2	2		
SOP3	Creative problem before	1.14	1	-2.23	0.02
	creative problem after	1.85	2		
SOP4	Creative problem before	0.42	0	-2.33	0.02
	Creative problem after	1.42	1		

Students were finally exposed to fully open design problems i.e. creative level problems. We calculated mean ranks of students for each sub-competency (Table 8.12) and compared SOP scores for creative design problem before (i.e. at the beginning of the study) and after 5 weeks of interaction with TELE-EDesC.

We found that there is significant difference between all sub-competency scores for creative design problem before training and after training {SOP1 (z=-2.33, p=0.03), SOP2 (z=-2.33, p=0.002), SOP3 (z=-2.23, 0.02) and SOP4 (z=-2.33, p=0.02)}.

Thus we see that an extended training with TELE-EDesC modules can help students develop "Structuring Open Problem (SOP)" design competency and help them to attempt higher level creative design problems.

This is reflected in SOP scores of students before and after training and progressive improvement is seen. SOP4 is seen to be hardest without training, but training can lead to development of SOP4 as well. This implies training with TELE-EDesC modules can prepare students for future learning. Learning Dialogs are able to trigger essential metacognitive processes of SOP competency for "Creative level" design problems.

This implies TELE-EDesC developed for different topics of analog electronics circuits is useful to develop SOP competency among students. When students are trained with these modules for extended periods (such as 5 weeks in this study), they can transfer SOP competency at creative level design problems.

8.4. Summary

This chapter mainly focused on extending the scope of TELE-EDesC along three dimensions, namely content, design competencies and design problem level. In terms of extending the content of TELE-EDesC, we found that the template developed in Chapter 5 can be used to create content for TELE-EDesC modules in topics beyond analog electronics. Two teachers applied template and successfully developed Learning Dialogs for the topics from their respective domains – microwave antenna and scheduling algorithms. In terms of extending TELE-EDesC to various design competencies, the pedagogical framework proposed in Chapter 5 is applied to develop Learning Dialogs for multiple representations (MR) design competency. Metacognitive processes, which is an intermediate step, are identified for competencies like Divergent Thinking, Convergent thinking and Information gathering. This chapter also showed that TELE-EDesC can be helpful for developing SOP competency for creative level design problem. Students were able to demonstrate SOP competency attainment for creative level design problems after trained with 6 TELE-EDesC modules in 3 topics, over a period of 5 weeks.

Chapter 9 discusses overall thesis implementation leading to conclusion and future scope of research work.

Chapter 9

Discussion and Conclusion

This concluding chapter of the thesis begins with an overview of the teaching-learning problem addressed, and the solution implemented (Section 9.1). Each research question posed and answered in Chapters 4-7 is examined and discussed (Section 9.2). Claims are made based on the results obtained from the empirical studies. The generalizability of the claims is explored, and an attempt is made to argue that the boundaries of the solution can be extended to newer topics and contexts (Section 9.3). This is followed by the limitations of the thesis (Section 9.4), and the contributions of the thesis for research as well as practice (Section 9.5). The chapter concludes with possible directions of future work (Section 9.6).

9.1. Overview of problem and solution

Engineering students should be prepared to demonstrate pan-domain thinking skills (Mishra, Koehler & Henrikson, 2011) such as problem estimation, problem posing, modelling, system thinking, and design thinking along with content knowledge. Engineering design is one of these thinking skills mentioned as important outcome of engineering education by ABET (ABET, 2012). A common concern from educationists and employers alike is the lack of engineering design thinking skill amongst graduating students. Engineering design thinking is blend of many complex cognitive processes which makes it difficult to teach. Development and assessment of such engineering design thinking skills is the research issue addressed in this thesis.

Engineering design thinking being complex, the first challenge is operationalisation of these skills, in such a way that we can track its development. We followed the approach of outcome based measurable competency (ABET 2000). First we identified the competency (through literature analysis) that reflect engineering design thinking; these competencies were: Structure Open problem (SOP), Information gathering (IG), Multiple Representations (MR), Divergent thinking (DIV) and Convergent thinking (CONV). We then operationalised them into measurable units that we called sub-competencies which we used as the basis to develop an assessment instrument. Valid, reliable, useable rubrics were developed to track students' achievement of engineering design competencies. We then designed, implemented and evaluated a technology enhanced learning (TEL) environment to help students develop these competencies. The pedagogical framework that emerged from this research process provides steps to design TEL environments for Engineering Design Competencies.

9.2. Answering Research Questions

The main research question in this thesis was: *"How to develop and assess engineering competencies?"* This research question is answered using Education Design Research Method which is recommended for addressing complex problems of education (Van den Akker et.al, 2012). EDR contains four phases such as problem analysis, prototype design, evaluation and refinement. The problem of developing engineering design thinking is analysed by analysis and synthesis of literature, and provided two research questions as

- *How to assess engineering design competencies?*
- *How to develop TEL environment to teach engineering design competencies?*

The second phase of EDR is to develop a prototype for the intervention. Backward design approach was applied for this phase. In backward design approach, assessment is designed first to decide desired outcomes (keeping the end in mind), followed by the design of the instructional intervention. The research question and constituent sub-research question at this stage were:

RQ.1: How to assess engineering design competencies?

RQ.1.1: What are the measurable units of engineering design competencies?

The measurable units of design competencies, referred as "sub-competencies", were identified by content analysis of expert's design problem solutions. Sub-competencies were identified and defined for all the engineering competencies: Structure Open problem (SOP), Multiple Representations (MR), Information gathering (IG), Divergent thinking (DIV), and Convergent thinking (CONV). These definitions formed the basis for the specific learning outcomes for each engineering design competency, which in turn formed the basis of the assessment rubrics we developed. The rubrics were later used to measure students' attainment of engineering design competencies, in particular, SOP competency which was the focus of the quantitative experiments (Chapters 6 & 7). The assessment rubrics for the above engineering design competencies were developed through iterative cycles of construction and validation. Research question of study is

RQ1.2: Are the rubrics scores valid reliable and useful to assess engineering design competencies?

The validity of the rubrics was established by empirical studies for content, construct and criterion validity (Docktor, 2009). The rubrics scores of students' design solutions were found to highly correlate with the overall, holistic, grades assigned to them by instructors. The inter-rater reliability of rubrics was established with 3 different ratters, in addition to the thesis author (kappa= 0.88). The usability and usefulness of the rubrics as an instrument to assess engineering design competencies was established (SUS score=72) by 7 engineering instructors.

While the rubrics were developed with the initial objective of assessment, their role went far beyond in the research in this thesis. The rubrics formed the backbone of the TELE-EDesC pedagogical design framework. They were the basis to develop learning outcomes of design competencies. They also guided the design process of Learning Dialogs, by incorporating formative assessment. An additional important role played by the rubrics was that of metacognitive scaffolds for students. The rubrics were provided to students for self-assessment within the Learning Dialogs, which helped students to not only to track their progress but also guided them towards the desired performance by way of transparent descriptive criteria. The most crucial use of the rubrics for students was in their development of SOP4 competency – 'write a structured problem statement'. The rubrics played the role of a coach to scaffold students' metacognitive process of "synthesis", which was critical in the development of SOP4 competency.

Once the assessment rubrics were developed, our goal was to design a TEL environment for students to develop engineering design competencies. The research question answered was:

RQ2: How to develop a TEL environment to teach engineering design competencies?

The process to develop a TEL environment for engineering design competencies emerged in the form of a pedagogical framework (Section 5.5, Table 5.5), from our initial cycles of design of TELE-EDesC. The framework helps the designers of such TEL environments to identify specific learning activities for various engineering design competencies, and provides steps and guidelines to create and sequence these learning activities into a learning module.

We applied this framework to develop TELE-EDesC modules for SOP design competency in topics of analog electronics. As recommended by the framework, the Learning Dialogs we developed for SOP competency were Decision Making Task Questions (DMTQ), Simulative Manipulations(SM), Concept Clarification Questions (CCQ), Self-assessment Rubrics, Controlled Animation (CANM), Capsule Recommendations (CR) and Information Box (Info Box).

The pedagogical framework was shown to be effective for designing TELE-EDesC modules in new domains. We used the framework to develop a template that guides instructors step-by-step in creating Learning Dialogs in their chosen topics. The template was used by two engineering instructors to create TELE-EDesC Learning Dialogs for SOP competency in their respective domains: Electrical Engineering - antenna design, Computer Science - scheduling algorithm. We also identified Learning Dialogs and underlying metacognitive processes for engineering design competencies other than SOP.

In the last part of this thesis, we conducted studies of learning effectiveness of TELE-EDesC modules and answered the research question:

RQ3: What is the effectiveness of TELE-EDesC to develop engineering design competencies?

We conducted quantitative quasi-experimental studies (N_{total}=295, $N_{expermental\text{-}group}$= 146, $N_{control\text{-}group}$=149) which indicated that students who learnt using TELE-EDesC modules attained a higher level of SOP competency as indicated by their rubrics scores on a post-test ($p<0.001$ in Mann Whitney tests), compared to students in the control group who studied using informative visualisations. These studies were conducted across 6 topics. In the above post-tests, students had to structure an innovative-level open-ended design problem in the same topic as the one they had learnt from in the TELE-EDesC module. We also conducted a longitudinal study over 5 weeks that showed that when students learnt with a series of TELE-EDesC modules (6 topics) they were able to structure an open design problem at the higher creative level. These studies indirectly validated the effectiveness of the pedagogical framework developed (answer to RQ2), as the TELE-EDesC modules were designed by applying the framework.

We also found that students' conceptual understanding of the topic alone was not sufficient to their succeeding in attainment of engineering design competencies. This is consistent with the experimental results for software design which indicates that an academic performance, seems to have little or no relationship to the quality of design produced (Eckerdal, 2006). To further explore which students were successful in attaining engineering design competencies and what led to their success, we conducted qualitative studies to answer the research question:

RQ.3.1: What is the difference between learning behaviours of successful and unsuccessful students when interacting with TELE-EDesC?

A qualitative analysis of students' screen-captures as they interacted with TELE-EDesC indicated that students who actively interacted with Learning Dialogs such as acting on feedback, examining implications of different alternatives in the decision making tasks attained desired learning outcomes (SOP competency), while students who answered question and did not read feedback, or used only few variations did not. The implication was that some students need to be explicitly guided to actively interact with all the Learning Dialogs of TELE-EDesC. Hence in future iterations of TELE-EDesC development, it would be desirable to include such guidelines for learners. We thus developed TELE-EDesC with refinement for catalysing the learning process of students. Self-assessment rubrics added to TELE-EDesC to self-tune their learning process with desired outcome using self-assessment rubrics.

Once we had evidence that students were able to demonstrate SOP competency in topics similar to the ones they learnt with TELE-EDesC, we tested to what extent they were able to transfer these competencies to new contexts. We were interested to know the role of rubrics in transfer of sub-competencies to new context.

RQ3.2. What is the role of self-assessment rubrics in transfer of sub-competencies to new context?

Students are able to transfer SOP design competency in new context under certain conditions. The condition in which TELE-EDesC included self-assessment rubrics supported transfer of SOP design competencies. The self-assessment rubrics of TELE-EDesC provided opportunity to students for thoughtful reflection and evaluate their learning. They prompt students to carry out formative assessment of their performance, monitor and revise their achievement level and plan their learning based on target level. This process of self-reflection prepared students for future learning (Bransford and Schwartz, 1999) and they are able to transfer the sub-competencies in new context.

Overall TELE-EDesC modules were shown to be effective to develop engineering design competencies among students. Learning Dialogs of design competencies trigger relevant design thinking processes which help students to attain design competencies. Fig. 9.1 shows an overview of the research questions, research methodology and contributions of thesis.

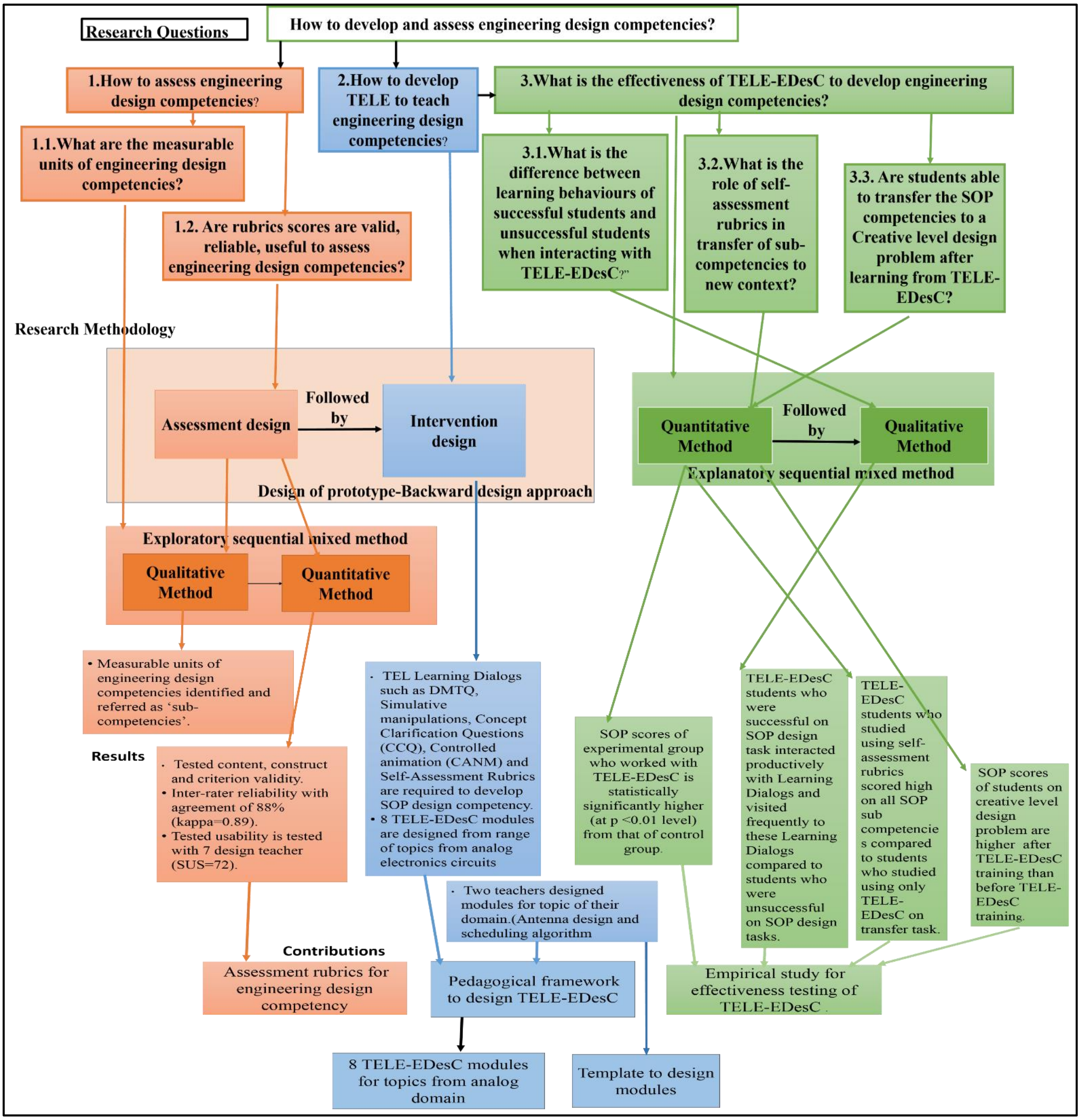


Fig. 9.1. Overview of research questions, methods, results and contributions of this thesis

9.3. Generalisability of TELE-EDesC

The central goal of this thesis is to develop and assess engineering design competencies among students, using a technology enhanced learning environment. In Chapter 1, we had initially proposed the scope of this thesis along three dimensions:

i) Domain content: Analog electronics circuits
ii) Design competencies for which learning materials for TELE-EDesC are developed: Structure Open Problem competency
iii) Level of design problems: Innovative level

In Chapter 8, we attempted to extend the above scope.

Domain content. We developed TELE-EDesC modules for topic from Analog electronics circuit domain. We developed modules for three topics (DC circuit design, Amplifier design and OP-AMP design). We tested all these topics using controlled experiments and found that TELE-EDesC modules develop SOP competence among students (Chapter 5, 6). In order to guide researchers, content developer and teachers we developed guidelines in the form of template. We applied template to develop modules for topic of power amplifier in analog circuit domain. Overall we developed modules for four topics from analog electronics to cover range of design problems in this course. In Chapter 8, we showed that two teachers developed modules for topic of antenna design and scheduling algorithm. Teachers were able to apply template appropriately and Learning Dialogs written by them were as per guidelines provided to them. Our claim is TELE-EDesC learning modules can be developed for topics from different courses. It is possible to conduct usefulness and usability study of template for teachers which may further help to decide guiding principles in development of content for various topics.

Design competencies. We showed the applicability of the pedagogical framework to design and develop TELE-EDesC learning modules in SOP competency (Chapter 5), and evaluated that the TELE-EDesC modules were effective in developing students' SOP competency. We also applied the framework to design TELE-EDesC learning modules for Multiple Representation competency (Chapter 8). These modules are developed and preliminary evaluation showed that pedagogical framework is useful for designing Learning

Dialogs of MR. Further, we partially applied the framework towards designing TELE-EDesC learning modules for other engineering design competencies such as convergent-divergent thinking. (In this thesis, we identified the underlying metacognitive processes for convergent-divergent thinking, but have not identified specific Learning Dialogs for this design competency). Thus we believe that the pedagogical framework is applicable for developing TEL environments for all engineering design competencies.

Level of design problems. The various quantitative and qualitative studies (Chapters 6, 7) showed that students develop SOP competency by learning with TELE-EDesC modules, that is, after interacting with 1-2 modules of TELE-EDesC in a topic, they are able to structure new innovative level problems in the same topic. We then increased the complexity of the design problem students had to structure. In Chapter 8, we showed a 5-week long intervention with TELE-EDesC learning modules was effective in students' being able to structure higher level (i.e. more open) design problems, namely, Creative level problems. Our claim is that the Learning Dialogs in TELE-EDesC trigger the underlying metacognitive processes required to attain SOP competency. Thus, we believe that after learning with TELE-EDesC over a period of time, students can internalize and apply these processes to structure newer, more challenging and more open, design problems so long as they are familiar with the domain concepts in that topic. This needs to be progressively tested.

Thus the work in this thesis is useful for:

i) Developing students' ability to structure open problems at various levels of 'openness', in topics related to electronics circuits.
ii) Assess students' engineering design competencies in all branches related to electronics / electrical engineering, and possibly other branches.
iii) Designing complete learning modules (including specific Learning Dialogs) for SOP competency by researchers or developers of TEL environments, in their topic of choice.
iv) Guide researchers and developers of TEL environments in designing learning modules for other engineering design competencies

The framework emerged from thesis provided guidance to identify metacognitive processes to achieve desired learning outcomes. Metacognitive processes were triggered by Learning Dialogs of TELE-EDesC. Framework provides mapping from learning outcomes to Learning

Dialogs. This framework was applied to design competencies like Multiple Representations, Information gathering, Convergent, Divergent thinking to identify metacognitive processes. For Multiple representations Learning Dialogs are identified. This works as look up table to develop TELE-EDesC modules for other competencies in future.

In order to help teachers and researcher to design TELE-EDesC modules for SOP, template is developed. Template helps to select content for TELE-EDesC and provides guidelines to write Learning Dialogs for SOP. Template was applied to design modules by teacher in their domain (microwave antenna design & computer scheduling task) and they were able to select content appropriately. 80% of Learning Dialogs written by teachers were accurate. This showed that modules for other topics can be developed. Since template is not our main product we have not done rigorous testing process here, instead we only want to find possibility to develop modules in other topics. Our results showed that TELE-EDesC modules for other topics than analog electronics can be designed using template of SOP.

9.4. Contribution of thesis

This thesis makes contributions to the field of technology enhanced learning and teaching in terms of products, processes and research knowledge based on empirical studies. The major contributions of the thesis are:

- *Product:* Eight TELE-EDesC modules have been developed for four topics for Structure Open Problem competency, in a range of problems that cover major topics in analog electronics circuit domain.
- *Product:* Assessment rubrics for engineering design competencies have been developed and validated for content, construct and criterion validity. Inter-rater reliability (kappa=0.89) and usability have been established (SUS= 72).
- *Process*: A pedagogical framework to design TELE-EDesC modules for developing students' engineering design competencies has been proposed and tested. The framework provides the steps to researchers to develop Learning Dialogs of a TEL environment for developing students' engineering design competencies. In particular, the framework prescribes specific Learning Dialogs (and guidelines to create them) for SOP competency- Decision making task questions (DMTQ), Simulative

manipulations, Concept clarification questions (CCQ), Self-assessment rubrics. Controlled Animation (CANM), Capsule Recommendations (CR) ,Information Box(Info Box)

- *Empirical study:* Effectiveness study of TELE-EDesC learning modules using quantitative and qualitative analysis is conducted. This study confirmed that Learning Dialogs prescribed by the framework are required to develop Structure Open Problem design competency.

The minor contributions of this thesis are:

- Important competencies and sub-competencies for engineering design thinking have been identified and operationalized into measurable learning outcomes, for domain of analog electronics circuits.
- A template is developed for teachers, content creators of TEL environments, and researchers to design TELE-EDesC modules for SOP in their respective domains. Template contain specific guidelines to prepare content and write Learning Dialogs

This thesis is one of the possible solutions to teaching-learning problem of engineering design thinking skill. It contributed to research in educational technology through instructional modules, assessment rubrics, pedagogical framework and template to write Learning Dialogs of SOP. The contributions of this thesis has implications for researchers, practitioners, TEL environment developers and students.

Assessment of engineering design is mostly through products developed by students at the end of the course (Sobek & Jain, 2004; Scott & Merwe, 2003; Brockman, 1996; Mankin, 2007). Assessment of student's development of design thinking skill progressively is a challenge as diverse opinion exists about what and how it should be assessed (Dym, 2005; Trevisan et al., 1999; Platanitis & Pop-Iliev, 2010; Platanitis, Pop-Iliev & Nokleby, 2009).). Engineering design competency rubrics developed in this thesis provides a way of assessing students' engineering design thinking by tracking competency development. One use of these rubrics are by instructors who wish to assess students' engineering design competencies. However, rubrics are not just an assessment instrument but are the backbone for developing the learning environment. Thus another potential 'consumer' of the rubrics developed in this thesis are designers of TEL environments for engineering design. Finally, and perhaps most importantly, the rubrics scaffold the self-regulation process of learners. The rubrics guide the entire teaching-learning process of design thinking by providing the desirable outcomes to attain the competency. They show progressive learning scales, thus helping students for self-assessment.

TELE-EDesC modules contribute to the body of self-learning resources for the problem definition phase of the engineering design thinking activity. Several existing TEL environments attempt to teach students problem-solving in general (Linn, Clark & Slotta, 2002; van Joolingen, de Jong, Lazonder, Savelsbergh & Manlove, 2004; Sun & Looi, 2012). This research work specifically concentrates on problem structuring aspect which is the vital competency in design thinking process. A conceptual contribution of this thesis is the identification of Learning Dialogs like Decision Making Task Questions, Simulative Manipulation, Information Agents and Capsule Recommendations, Self-Assessment Rubrics to develop SOP competency. Design and testing of Learning Dialogs showed that SOP design competency can be triggered using these Dialogs. These Learning dialogs in fact make the design thinking process visible to learner through different learning actions and precise feedback on every action. Thus identification of accurate Dialogs to trigger the metacognitive process was crucial in the TELE-EDesC design. TELE-EDesC are useful self- learning resource for students. This resource also can be used by design teachers as pre-lab self-learning activity to train students for design thinking before exposing them to real world problems.

The design process of TELE-EDesC new or unknown as TELE-EDesC is a product of this research work. Thus there is need to define the systematic process of TELE-EDesC development which is a pedagogical framework. Pedagogical framework guides processes of identification of Learning Dialogs for engineering design competencies. For TEL environment developers and researchers it is useful for identification of essential Learning Dialogs based on learning outcomes of design competencies. This framework was applied to identify Learning Dialogs of SOP. TELE-EDesC modules are designed by creating content based Learning Dialogs. The template is developed to guide module development. It contains step-by-step guidelines for content development and creating Learning Dialogs. These are useful for instructors and TEL environment designers to develop the modules for their subjects to teach SOP competency.

This thesis has contributed a framework as well as products to analyse and make sense of the complex cognitive process of design thinking, using an outcome-based approach that identifies measurable competencies. The products help students develop these competencies and have been empirically tested it for a specific competency i.e. SOP within engineering design in a specific subject (analog electronics). We also attempt to provide ways of generalizing the products and process to other subjects and possibly to other competencies in engineering design.

9.5. Limitations

While this thesis has produced encouraging findings and useful contributions, its limitations needs to be identified and analysed.

One limitation of this thesis stems from the approach to the operationalization of design thinking that we chose (Section 2.2). Since we chose to consider the complex concept of design thinking in learners in terms of competencies and its constituent sub-competencies, what we can claim is that students who learnt from TELE-EDesC have developed certain competencies which are important in process of doing engineering design. What we cannot claim is that students have become better designers overnight. However, by improving these competencies it may be possible that students' final design products or their design thinking skills get enhanced. We have preliminary evidence for this from the longitudinal experiment in which students were trained with TELE-EDesC modules for 3 weeks and then SOP task was given for creative design problem. Students' confidence level improved and their attempts to structure creative design problem was successful. But this is yet to be tested rigorously.

Another limitation of this thesis is that large parts of the thesis have focussed on one competency related to engineering design - structure open problem competency. The various engineering design competencies identified (Chapter 2) were structure open problem, multiple representation, information gathering and convergent-divergent thinking. Assessment rubrics were developed for all competencies. However, Learning Dialogs in TELE-EDesC were developed and extensively tested for structure open problem competency alone. Similarly, the pedagogical framework for developing TELE-EDesC modules has been applied to structure open problem as well as multiple representation for identifying Learning Dialogs. On the other hand, TELE-EDesC modules are designed only for SOP competency.

The sample considered in all empirical studies in this thesis is mostly second year undergraduate students. Thus generalizability of sample is restricted to second or third year undergraduate students who are novices in the process of engineering design. Another limitation is if students are not motivated or interested in self-learning, then TELE-EDesC may not be useful way to teach engineering design thinking skill.

Most of the topics of TELE-EDesC, as well as assessment rubrics were developed in the context of electronics and allied streams, thus its generalizability to other branches of engineering may not be valid. Whether the pedagogical framework, which offers the steps to design TELE-EDesC modules, or assessment rubrics are applicable to design in other branches of engineering is yet to be tested.

In terms of methodology, the dominant research design used was controlled experiments and quantitative analysis. While this research method allowed us to determine whether TELE-EDesC was effective compared to other interventions, a quantitative design is limited and not suitable to answer '*why*' questions, such as 'why (or how come) was TELE-EDesC effective'. Our mixed method design which did contain a qualitative strand (screen capture analysis) addressed this issue to some extent. However, a richer and deeper qualitative study is required to understand what makes TEL environments effective, how learners' manipulation of technology tools affects their cognitive structures and so on.

Another methodological limitation was that TELE-EDesC was mostly implemented only for short durations. In most studies (Chapters 6 & 7), students learnt with TELE-EDesC for one or two topics, that is, 30 minutes to an hour before testing. The exception was the study on students' ability to transfer SOP competency to creative design problems (Section 8.1) in which students learnt with TELE-EDesC over an extended period of 5 weeks and 6 modules. Further, testing was done immediately after students interacted with TELE-EDesC. There was no study in this thesis that can claim that students are able to apply engineering design competencies after an elapsed time beyond their initial interaction with TELE-EDesC.

More implementation and evaluation is required to test for how long students need to initially interact with TELE-EDesC, and for how long they are able to retain the ability to apply the competencies they developed.

TELE-EDesC effectiveness for learning was evaluated via a post-test, in which open-ended answers of students were evaluated manually based on rubrics. A more desirable option would be to integrate the assessment within the TEL environment. However, currently available assessment methods and corresponding technology affordances do not provide a means for technology-enabled assessment of engineering design competencies.

9.6. Future Work

9.6.1. Expansion of pedagogical framework to develop TEL environments for various thinking skills

Engineering design thinking was identified as one of the important thinking skills for students. A pedagogical framework has been proposed in this thesis to develop TEL environments for student learning of engineering design competencies. This framework has been applied for SOP competency, by developing TELE-EDesC modules for SOP in various analog electronics topics. A template was developed based on the pedagogical framework that guides instructors to create TELE-EDesC learning modules for SOP.

As a first future step, the template can be tested with instructors in different domains to establish its usability and usefulness. This could lead to extending TELE-EDesC modules for SOP in various topics and domains. In order to train teachers without spending much time in training following activities can be done

1) More detailing of guidelines with multiple numbers of examples could be designed.

2) Videos could be designed to train teachers to develop their TELE-EDesC modules.

3) Spoken tutorials could be developed for training teachers.

In future it is possible to come up with guiding principles for teachers and researchers to design TELE-EDesC. These principles can be developed using validated pedagogical framework and teacher module writing template. Thus design of TELE-EDesC and identification of guiding principles to design TELE-EDesC can be one of the future research area emerged from this thesis.

The extension of the pedagogical framework is another prominent direction of future research. Proposed Learning Dialogs (for MR) and metacognitive processes (for other competencies like IG, CONV, and DIV) can be validated by designing and testing TELE-EDesC modules. Once a detailed framework is created for different engineering design competencies, TELE-EDesC learning modules can be developed and tested.

To further expand the usefulness of the pedagogical framework, a possible direction of research is the application of the framework to develop TEL environments for other thinking skills such as system thinking, algorithmic thinking etc. If measurable learning outcomes are known for these thinking skills then framework is applicable. Learning outcomes of this thinking skill can be used to identify learning dialogs of the TEL environment. Further modules can be designed and tested for learning effectiveness. Thus entire research work of this thesis can be replicated to develop TEL environment for other thinking skills than engineering design thinking skill. This will establish generalisability of framework with improved utility.

9.6.2. Collaborative learning of engineering design competencies

We focussed on individual students' acquisition of engineering design competencies in this entire research. But in engineering design teamwork is emphasised and is one of the desired educational outcomes of engineering students (ABET, 2012). Teamwork can be developed using collaborative learning strategy. Collaborative learning is considered as coordinated synchronous activity (Stahl et.al, 2006) in which individuals negotiate and share concepts of problem solving. Computer supported collaborative learning i.e. CSCL is part of many TEL environments like WISE, GO-LAB, and WiMVT etc. Addition of collaborative learning proved beneficial in development of scientific inquiry skills (Linn and Slotta, 2004; Sun et.al, 2013), argumentation skill (Chen et.al, 2013). Engineering design is also one of the thinking skill which includes ill structured problem solving, decision making, and inquiry skills (Dym, 2005).). It may be fruitful to add collaborative component in TEL environment to support teamwork in design tasks which may help students to contrast and compare each other's design ideas for real world design problems. In future direction of work the possibility to add collaboration along with individual development need to research.

Learning Dialogs can be designed to initiate collaboration activity for design competencies.Collaborative learning could be facilitated by adding shared learning space(Van Joolingen et.al,2005) in TELE-EDesC. The shared space could be designed in a such a way that learners can discuss ideas through chat window. TELE-EDesC includes learning dialogs like DMTQ in which decision making questions are provided at decision step. The possible modification in these dialogs is through peer instruction strategy. DMTQ of TELE-EDesC could be modified by allowing learners to vote for the answers individually and then allowing them to discuss the answers through chat window. The facility to revote could be added into environment and the responses of learners could be analysed through ISAT(Majumdar & Iyer, 2014) tool. The feedback of DMTQ as pedagogical agent could be displayed based on response analysis of learners. The shared space of TELE-EDesC could contain chat window for disussing reasoning of decision options,revote button to submit changed decision and feedback window to support the decision.

Pedagogical framework could be modified to accommodate collaborative component and its effect on development of design thinking can be tested.

9.6.3. Establishing Rubrics utility for other branches of engineering

The rubrics developed in this study were tested for design competencies for analog electronics and allied domains like digital, communication, microwave etc. Utility of rubrics can be established for assessing design problems of other branches of engineering such as mechanical, civil, computer science etc.

Rubrics formed the backbone of our research as they guided the learning process making attainment of competence visible to students. Rubrics are not just a scoring tool but are a guiding tool which make expected learning outcome visible to students, as well as guide researchers, instructors and curriculum developers in designing their learning materials. Thus development of rubrics for design competencies in other branches can help researchers to develop TELE-EDesC using pedagogical framework. This can be seen as expansion of pedagogical framework for other branches of engineering.

This list of possible directions of future work is merely indicative, and not exhaustive. The above directions can be considered to be one starting point in the rich field of designing technology enhanced learning solutions for thinking skills.

Appendix

Appendix-I

Table A1.1: Analysis of research papers for mapping engineering design competencies

Common meaning codes	**Categories and Levels for Defining Engineering Design Program Outcomes [Davis, Crain,Calkins, Gentili, Trevisan (1997)]**	**Competency requirements in the Greenfield paradigm: the manufacturing engineer of the 21st century. (Plonka, Hillman, Clarke & Taraman, K. (1994, November).**	**Design engineering competencies: future requirements and predicted changes in the forthcoming decade(Robinson,Sparrow,Chris and Birdi(2005)**	**Learning Engineering: Design, Languages, and Experiences--Clive L. Dym(2003) 2-Engineering Design Thinking, Teaching, and Learning-Dym ,Agogino, Ozgur, Frey &Leifer (2005)**	**A comparison of freshman and senior engineering design processes- Atman, Chimka, Bursic and Nachtmann.(1999)**
Problem Identified and defined--PROB	PROBLEM DEFINITION-For a given problem situation, prepare a goal statement with specific technical and nontechnical, measurable, criteria to be satisfied in a successful design solution	Solve unstructured problems: Identify Problems Develop Specifications and Requirements	Personal attributes	Maintain sight of the big picture by including systems thinking and systems design.	Problem scoping means adequately setting up the problem before analysis begins. Poor problem scoping has been shown to lead to poor performance.
Information collected-INFO	INFORMATION GATHERING- Use various sources and techniques to identify, obtain, and determine relevance of information needed at	Access Information and Knowledge			Seniors gathered more information and covered more categories than the

	different stages of the design process				freshmen.
Solutions consideration-SOLN	Idea Generation-Select and employ appropriate techniques effectively for creating numerous innovative yet relevant ideas at various stages throughout the design process		project management	Tolerate ambiguity that shows up in viewing design as inquiry or as an iterative loop of divergent-convergent thinking;	Seniors would generate more alternative solutions than the freshmen. Seniors who considered a greater number of alternative solutions generated a higher quality design.
Evaluated solutions using criteria-EVL	EVALUATION AND DECISION MAKING-Select and utilize appropriate methods for evaluating ideas and making design decisions based on established criteria	Develop predictive models	Cognitive strategies Cognitive abilities	; handle uncertainty; make decisions;	Seniors did have both a higher number of transitions between design steps and a higher number of transitions per minute.
Product development-PROD	IMPLEMENTATION-Define, interpret, and follow instructions for advancing a design to a stage of usefulness to prospective clientele	Perform experiments	Technical abilities		On average, seniors spent significantly more time than the freshmen on the final steps in the project realization stage of the design process.
Communicate-COMN	COMMUNICATION-Accurately and efficiently exchange technical and nontechnical information among individuals with widely varying backgrounds, using appropriate methods and forms	Know yourself and work with others: Examine and Evolve Self. Act ethically Communicate	communication	Think and communicate in the several languages of design.	
Teamwork-TER	TEAMWORK-Work with others of diverse backgrounds in informal groups or structured teams to produce collective achievements beyond those which could be accomplished individually	Team- Participate effectively in work teams Develop awareness skills for appreciating readiness of others for receiving information		think as part of a team in a social process;	
Iterations-ITR	PROCESS IMPROVEMENT-Work with others of diverse backgrounds in informal groups or structured teams to produce collective achievements beyond those which could be accomplished individually				

Common meaning codes	Educating effective engineering designers: the role of reflective practice-- Adams, Turns and Atman(2003)	Concept generation and sketching :correlation with design outcome(Maria Yang(2003)	Expertise in design: an overview-Nigel Cross(2004)	Design abilities (Sheppard & Jenison, 1997)	Design problem activities (Aurisicchio et al., 2007)
Problem Identified and defined--PROB	Reflective practitioner behaves as if problem setting is as important as problem solving		Expert designer Structuring and formulating the problem	Define and formulate an open-ended and/or under defined problem, including specifications	Designer frames the problem with broader view and connects different issues to create chunks.
Information collected-INFO	gathering information on a just-in-time basis			Generate alternate solutions Use analysis to support synthesis Identify methods or approaches suitable for design Identify critical technology and approaches, stay abreast of change in professional practice	Generation and establishment of criteria
Visual representations-VISUA		Concept quantity, as measured through sketches, is significantly correlated to design outcome, as measured by design grades, under two conditions. First, only sketch volume generated in the first quarter of the design cycle correlates significantly. Second, the sketches must include dimensions.		Think with a systems orientation, consider needs of and integrate various facets of the problem Use a systematic problem solving approach Recognize the need for and implement iteration	Evaluation and decision steps of design activity
Solutions consideration-SOLN	Transition activity is suggestive of the structure of this process: more advanced students and those who produced higher quality designs were more likely to 'move'		Experts think of alternate solutions	Build hardware to prototype ideas Trouble-shoot and test hardware	

	to different design activities frequently throughout the task.				

Common meaning codes	**An Industrial Case Study: Identification of Competencies of Design Engineers (Saeema Ahmed,2007)**	**Cognitive Characteristics and design creativity: An experimental study YONG SE KIM,MI HYUN KIM SUN TAI JIN**	**Design: one, but in different forms (Visser, W. (2009).**	**A creativity-based design process for innovative product design Shih-Wen Hsiao(Jyh-Rong Chou)**	**MODELLING ITERATION IN ENGINEERING DESIGN David C. Wynn, Claudia M. Eckert and P. John Clarkson**
Problem Identified and defined—PROB Information collected-INFO	Knowledge about product like explanation, understanding and insights	Constructive perception is the ability to link reorganization of perceived information to conceptual process of finding meaningful interpretation	Problem solving activity based on design specifications	Product design is a goal-directed problem-solving Activity. The convergent stage is an integration and evaluation process for finding applicable sub-solutions and optimal design solutions, described as ‘‘testing to discover the results of putting the new arrangement into practice’’.	Concurrent, iterative exploration of problem and solution spaces is fundamental to the creative problem-solving process
Solutions consideration-SOLN	Knowledge of specific strategies applied in product development	Idea generation	Analysis, synthesis and evaluation are decomposition of design process. Designer transit between optimum value and best possible solution. Designers often tend to generate, at the very start of a project, a few simple objectives in order to create an initial solution kernel	Divergence- The divergent stage is an analytic process for searching the problem space, which can be described as ‘‘breaking the design problem into pieces’’.	Solution-oriented perspective, designing involves a repeated process of solution space divergence (during synthesis) followed by convergence (during evaluation
Visual representations-VISUA		The ability of a designer to visualize and reason about geometric aspects of physical objects			
Product development-PROD	Realization of product.		Designers constantly generate new task goals and redefine task constraints.	Transformation stage is a synthetic process for generating the solution space, characterized as ‘‘putting the pieces together in new ways’’.	

Common meaning codes	THE ROLE OF KNOWLEDGE AND EXPERIENCE IN ENGINEERING DESIGN Ahmed Hacker and Wallace(2005)	On synthesis in the later phases of the mechanical engineering design process Motte (2006)	Design Thinking in Engineering Education and its Adoption in Technology-driven Startups Açar,. Rother	Design Cognition: Results From Protocol And Other Empirical Studies Of Design Activity Nigel Cross(2007)	A SITUATED QUESTION-DRIVEN AND MODEL-BASED APPROACH TO DESIGN REASONING Dr. Ulf Sellgren(2005)
Solutions consideration-SOLN	Conceptual design -The designer is dealing with the whole product or whole assemblies and works from a blank sheet of paper, generating and evaluating several ideas.	Organization of design tasks ,application of basic rules ,principles ,guidelines, basic design activities	Integrative thinking is combination of integration of analytical and intuitive thinking understand phase of the process constitutes the intensive preoccupation with a problem.	. Setting and changing goals are inherent elements of design activity.	Analyse each question and specify the requirements for a target model.
Problem Identified and defined—PROB Information collected-INFO	Investigating and identifying the problem: Investigative and diagnostic work to identify the problem and may be applied to major quality failures. Detailed design: The knowledge required to define specific components including technical drawings and specifying manufacturing requirements Design for X: Knowledge to improve a design from	Design operations and skills for problem solving	Observe phase is used to correlate the findings of the previous step with observations out in the field. This leads to collection of information.	Successful design behaviour is based not on extensive problem analysis, but on adequate 'problem scoping' and on a focused or directed approach to gathering problem information and prioritizing criteria	Define the context-dependent engineering problem and reformulate it as one or several question(s). The context may for example be a stored product model of an artefact.

	a particular perspective, e.g. cost or quality not necessarily employing a formal design for x method or tool. Design for service Considering the product through its service i.e. once released, for example inspection or monitoring components for wear limits, etc. .				
Solutions consideration-SOLN	Analyze and Verify The knowledge required to analyses and verify a design, this may be conducted by the designer. Sufficient knowledge is required to be able to set up any necessary tests and to be able to challenge results from a formal analysis. Compliance with standards Knowledge to ensure design complies with standards and legislation	Basic cognitive skills like induction ,deduction, abstraction ,perception, Imagery attention	After gathering information from a variety of perspectives, the team analyses the collected data and approaches the problem from the point of view of the user.	Experience in a specific problem domain enables designers to move quickly to identifying a problem 'frame' and proposing a solution conjecture	Synthesize (i.e., configure) a specific systems model that available knowledge suggests will satisfy the requirements.

Solution consideration-SOLUN	. Managing requirements and assessing the risk of these requirements not being achieved for each component. Engineering processes and methods and tools: Knowledge of the impact of engineering processes, methods and tools. Managing time and cost requirements Designers ability to deliver design to schedule and cost. Managing resources Knowledge of line management, e.g. setting objectives, training, etc.		Ideate notions by using a variety of creativity techniques.	The designer's attention oscillates between the two, forming partial structuring of the two 'spaces' of problem and solution.	
Product development-PROD	Knowledge of Assembly: Knowledge of how the product will be assembled and of assembly plans Physical integration Ensuring that interfacing components physically fit together		Develop prototype ,test and iterate		

Common meaning codes	**WEB-BASED TEACHING OF OPEN-ENDED MULTIDISCIPLINARY ENGINEERING DESIGN PROBLEMS J.-M. Brault, P. Medellı´n Mila´n, M. Pico´ n-Nu´n˜ ez, M. El-Halwagi4, J. Heitmann, J. Thibault and P. Stuart,(2007)**		
	NSERC, 2004	Kishline et al., 1998	Eder et al., 2004
Problem Identified and defined—PROB Information collected-INFO	General knowledge	General knowledge	Branch or subject related competency
Solutions consideration-SOLN	Specific knowledge in a professional environment	Conduct experiments, analysis/ interpretation	Systems related competency
Solution consideration-SOLUN	Knowledge of procedures	Design a system, component, or process	Methods related competency
Product development-PROD	Operational skills	Using techniques, skills, and modern tools	Heuristic or practice related competency
Communication-COMN	Cognitive skills	Understanding of professional, ethical and social responsibilities	Personal and social competency
Teamwork-TER	Experiential skill social/personal skill	Communication teamwork(multidisciplinary)	

Table A1.2: Rubrics to assess Engineering Design Competencies

Structure Open Problem (SOP) - Ability to structure open problem

Sub-competencies	Target Performance(3)	Needs improvement(2)	Inadequate(1)	Missing(0)
SOP1-Identification of specifications- Is able to extract required specifications from given open ended problem	All the specifications identified and interpreted accurately	An attempt is made to identify specification Most of them identified but few hidden ones missing or needs more interpretation (like frequencies identified but B.W not calculated or mentioned.)	An attempt is made but specifications identified are most of them are wrong or incomplete.	No attempt is made to extract specifications
SOP2- Structure problem using specifications- Is able to structure open problem using specifications	All the specifications are used to take decisions to structure problem. All interconnections of the system are identified based on given and identified specifications such as the decision related to requirement of two stages based on gain requirement is identified.	An attempt is made to use specifications correctly but some minor specifications are not used for decision making such as which active device should be connected first is not considered while structuring the problem.	An attempt is made to use specifications but specifications are wrongly applied or some required specifications not applied to make decisions.	No attempt is made to use specification or identify structure
SOP3- Order design step sequence- Is able to sequence order of design steps based on specifications	All major and minor design steps are identified and sequenced correctly	Most of the designs steps are identified and identified steps are sequenced correctly. Few minor steps are missing or not sequenced such as sequence of design stages of amplifier is not correct or not given consideration at all.	Design steps are not at all sequenced or all identified steps are wrong	No attempt is made to write design steps
SOP4- Writing structured design problem- Is able to write structured design problem statement	Problem statement is written clearly with all details related to identified specifications, identified devices structures, design steps etc.	Problem statement is written clearly but few minor details like number of stages or which device etc. are missing,	Problem statement is not written clearly but scattered information is available	No attempt to write word statement. or no scattered information is available

Multiple Representations (MR)—Ability to represent information in multiple ways

Sub-competencies	**Target Performance(3)**	**Needs improvement(2)**	**Inadequate(1)**	**Missing(0)**
MR1- Construction of representation- Is able to construct representations for given problem.	Constructions are valid as per required problem .All primary and secondary details are present	An attempt is made to draw constructions, all primary information is represented in the constructions, but few secondary details are missing or drawn wrongly.	An attempt made to construct representations but wrong or incomplete constructions.	No attempt to construct representations
MR2- Consistency of representations- Is able to maintain consistency between different representations in the problem.	Representations are mostly consistent with each other with minor discrepancies such circuit diagram show resistance and is not calculated in mathematical representations.	Representations mostly inconsistent or incomplete	No attempt is made to draw consistent representations	All representations constructed are consistent with each other in major and minor details
MR3- Use of representation- Is able to use representations to solve problems	Question is answered correctly with the use of a representation other than a mathematical	Question is answered correctly without the use of a representation	Question is answered incorrectly	No attempt is made to answer the problem

Information Gathering (IG) - Able to gather appropriate information

Sub-competencies	Target Performance(3)	Needs improvement(2)	Inadequate(1)	Missing(0)
IG1-Identification of information source-- Is able to identify sources of information relevant for given problem	All the relevant sources of information for given problem are identified.	Most of the sources of information are identified and relevant. Few secondary sources are missing or irrelevant.	Sources of information identified but all the sources are irrelevant	No attempt to find sources of information.
IG2-Use of sources of information- Is able to find appropriate and all information from the source	All required information is found accurately.	An attempt to extract all required information. Information written is correct but some information missing.	An attempt to find Information but identified wrong information.	No attempt to find information from the source.

Think Divergent (DIV) --Think for divergent solutions

Sub-competencies	**Target Performance(3)**	**Needs improvement(2)**	**Inadequate(1)**	**Missing(0)**
DIV 1-Is able to write multiple solution ideas for given problem	All multiple solutions with minute details are written so that solution ideas are testable	Multiple solution ideas are written and they are appropriate. But solution ideas miss some secondary details making solution ideas insufficient e.g. in the solution amplifier design is mentioned but which amplifier or its configuration not specified.	Multiple solution ideas are written but they are not appropriate	No attempt made to write multiple solution ideas for given problem
DIV2-Is able consider variations in the specifications to write multiple solutions	All specifications with its variations are considered while writing multiple solution ideas.	Most of the important variations in the specifications are considered to write solution ideas, but few secondary variations are not considered such as Bandwidth and gain relation is given considerations but cascading of stages is not considered.	Wrong variations in the specifications are considered to write multiple solutions	No attempt to consider variations in the specifications
DIV3- Is able to consider constraints to write multiple solutions	All constraint with details are considered while writing multiple solutions	Multiple solutions based on constraints are written and appropriate .All major constraints were identified but few minor ones are missing e.g. for amplifier practical availability of input voltage range is not taken into consideration thus will pose limitation on design.	Multiple solutions are written but they are not satisfying the constraints	No attempt made to write multiple solution ideas
DIV4-Is able to analyse multiple solutions based on pros and cons	All suggested solutions are analysed with all details.	Multiple solutions analysed based on pros and cons, all suggested solutions are appropriate. But analysis does not consider minor details e.g. While analysing amplifier, temperature effect on active device is not taken into account.	Multiple solutions suggested but analysis is wrong or incomplete.	No attempt made to analyse multiple solutions based on pros and cons.

DIV5-Is able to evaluate solution using alternate problem solving methods.	All problem solving methods are applied correctly. All parameters calculated are correct to last detail	Solution is analysed properly using different methods but few calculations are wrong or incomplete.	Solution is analysed using different methods but methods are wrong or incomplete.	No attempt made to analyse solution using different problem solving methods

Convergent Thinking (CONV)—Able to think convergent

Sub-competencies	Target Performance(3)	Needs improvement(2)	Inadequate(1)	Missing(0)
CONV1-Is able to select appropriate solution based on pros-cons analysis.	Solution selected is appropriate and contains all major and minor advantages and disadvantages.	Solution selected is correct but some minor disadvantages are missing(no consideration to temp variation)	Selected solution is wrong or incomplete.	No attempt to select the solution based on pros and cons analysis
CONV2-Is able to justify chosen solution.	Selected solution is justified accurately and attention is given to all minute details	Most of solution parts are justified accurately but few minor parts are not justified or wrongly justified .e.g. why to design 2nd stage initially and then go for first stage.	Wrong or incomplete justification is given for selected solution	No attempt to justify solution
CONV3-Is able to select solution based on principles.	Solution selected is appropriate all major and minor principles are considered while selecting the solution.	Most of the principles are considered for solution. Selected principles are applied correctly. But minor details not considered or applied wrongly. E.g. While calculating capacitor for 2 stage amplifier load for first stage is not considered.	Most of the required principles are not considered for selected solution or principles are wrong or wrongly applied.	Solution selected is irrelevant. No attempt to consider principle.
CONV4-Is able to make suitable and valid assumptions while selecting solution	All assumptions are written	Most of the assumptions are written but few of them are missing .(selection of practical values of resistance)	Wrong or incomplete assumptions	No attempt to write assumptions
CONV5-Is able to justify assumptions.	All assumptions primary as well as secondary are justified	Most of the assumptions are justified but few minor ones missing like how supply voltage is selected is not written.	Wrong or incomplete justification of assumptions	No attempt to justify assumptions

CONV6-Is able to work out overall complete solution which works out as per requirement	. The entire solution contains all required design steps all intercommoned systems and solution is as per requirement	Most part of the worked out solution are correct and complete but few secondary parts are incomplete or wrong	The solution worked out is not as per requirements or incomplete	No attempt is made to work out the solution

Appendix-II

Screenshots of TELE-EDesC Learning Material

All actual TELE-EDesC learning modules are at www.et.iitb.ac.in/~madhuri/<resources>

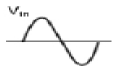
2.1. Modules 1 and 2 - DC circuit design

Introduction to concepts in dc bias circuit design of the amplifier (BJT CE amplifier design-Voltage divider bias)

Outline

- Concept of faithful amplification
- Identification of dc circuits
- What is Q point?
- How to measure and locate Q point?
- Interpret location of Q point

Concept of faithful amplification

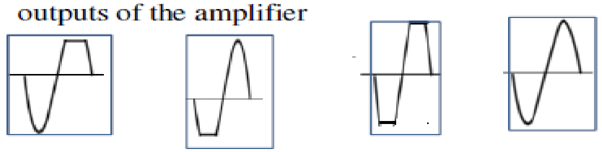
- The major goal of amplifier is to amplify applied input signal **faithfully.**
- When  is applied to the amplifier

then different types of output waveforms are possible .

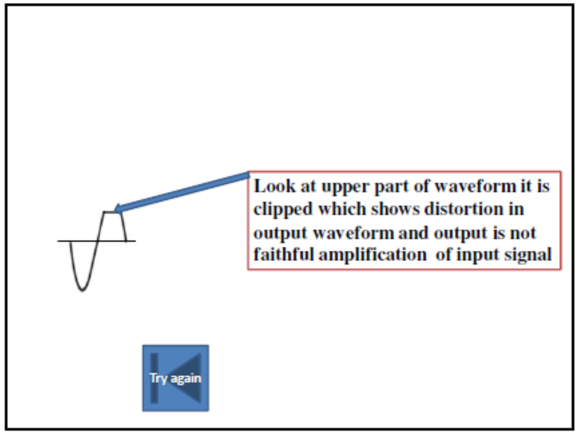
Let us find out what are the possibilities

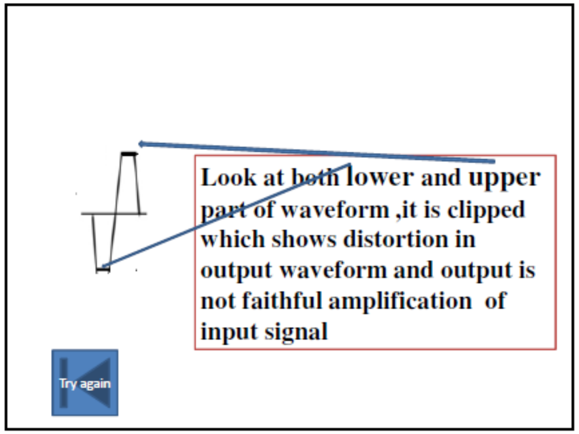
Faithful amplification-key specification

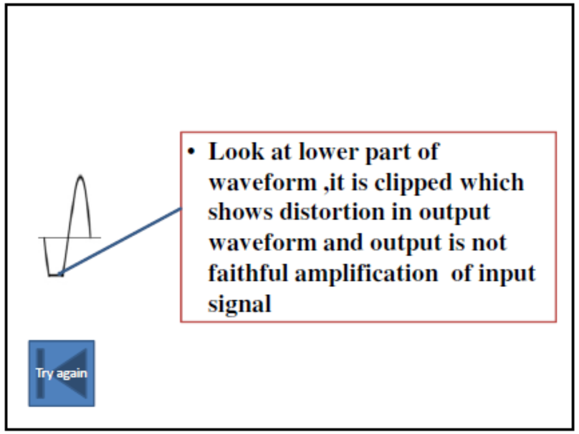
- The waveforms shown below are possible outputs of the amplifier

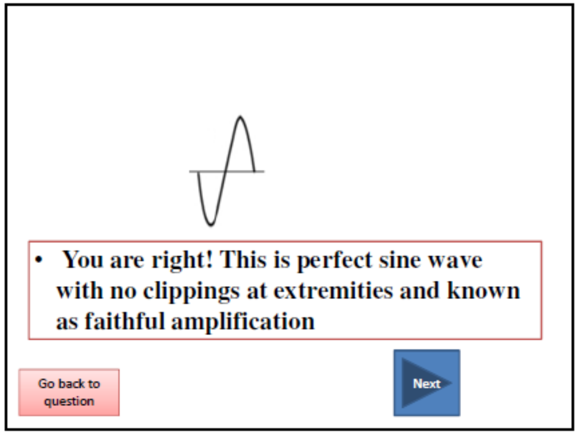


- Can you decide which of the above waveform represents faithful amplification of applied input signal( )?
- **(click on the waveform to select answer)**


Look at upper part of waveform it is clipped which shows distortion in output waveform and output is not faithful amplification of input signal
Try again


Look at both lower and upper part of waveform ,it is clipped which shows distortion in output waveform and output is not faithful amplification of input signal
Try again


• Look at lower part of waveform ,it is clipped which shows distortion in output waveform and output is not faithful amplification of input signal
Try again


• You are right! This is perfect sine wave with no clippings at extremities and known as faithful amplification
Go back to question
Next

Essential components to decide faithful amplification

- This combination of ac and dc circuit helps to decide only one parameter required to predict faithful amplification and thus not sufficient.

Try again

For BJT amplifier circuit faithful amplification can be predicted from

a)Amplitude of input signal and dc bias circuit

b)Dc bias circuit and ac circuit

c)Ac circuit and amplitude of input signal

- For this combination, amplitude of input signal is partially useful to decide faithful amplification but not complete specification and ac circuit alone is not sufficient ,it needs dc circuit to decide other parameter required to predict faithful amplification.

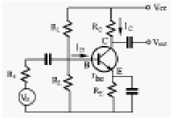
Try again

- You are right !
- Faithful amplification of the amplifier can be predicted from dc bias circuit and input signal amplitude.

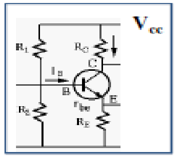
Go back to question

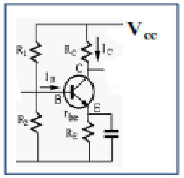
Next

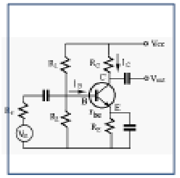
- For the given CE amplifier circuit identify which is appropriate dc circuit?



Select option by clicking on the circuit below







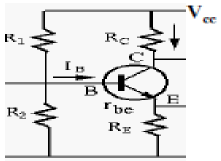
Identification of dc circuits

We will study effect of dc bias circuit on amplifier design
Let us find what is dc bias circuit

- In the selected circuit capacitors are present ,but for dc condition you need to open circuit capacitors and only resistors in the circuit will remain.

Try again

- You are right! . For dc condition all capacitors open circuited and only resistors in the circuit will remain. The circuit for dc conditions is



Go back to question

Next

Q . Which of the following do you think is useful to predict faithful amplification?

(click the box to select option)

- Value of β_{dc}
- Resistor values
- Q point location

Dc circuit parameter

Let us find what are important parameters of dc circuit to decide faithful amplification

- The values are helpful in calculating current and voltage values of the dc circuit but are not useful to predict faithful amplification

Try again

- You are right!
  Faithful amplification depends on location of Q point

Go back to question

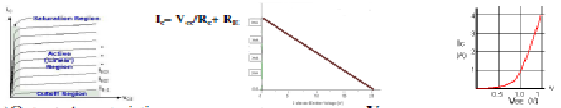
Next

- **You are right partially. One of the important characteristics to locate Q point is output characteristics ,but not sufficient to locate Q point.**

Select other options

How to locate Q point?

- To locate Q point which of the following characteristics are important?



a)Output characteristics b)Load Line V_{cc} c)Input characteristics

- (Select options by clicking the buttons)

- Only a
- only b
- only c
- a&b both
- a & c both
- b&c both

Input characteristics are useful to locate Q point partially (i.e. value of IBQ)but are not useful to find other values of Q point(V_{CEQ},I_{CQ})

Try again

Animation below will show how Q point is located

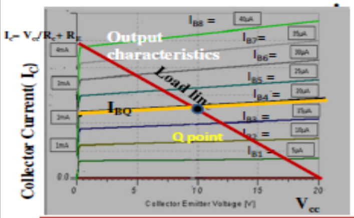
- 1.To locate Q point we need to draw Output characteristics
- **Output characteristics** – This is a set of characteristics . For each fixed value of base current(I_B) the relation between collector to emitter voltage(V_{CE}) and collector current(I_C) is plotted .

2.Superimpose load line on the output characteristics

Load Line—The line joining voltage V_{cc} and current $I_c = V_{cc}/R_c + R_E$

3.Mark I_{BQ} characteristics

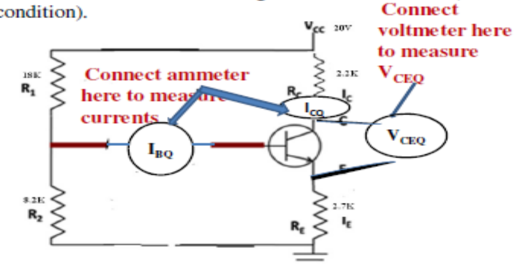
I_{BQ}—Base current of the given circuit under no signal condition. This is also known as dc bias current. I_{BQ} characteristics are output characteristics for I_{BQ}



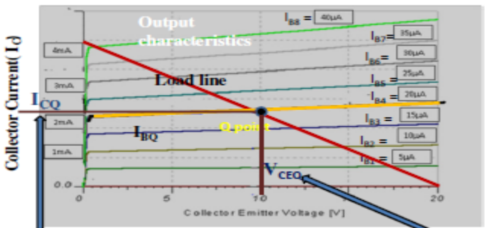
The point of intersection of I_{BQ} characteristics and load line is "Qpoint"
"Q point" is thus point on the load line representing dc bias conditions of the amplifier circuit

How to measure Q point

- To measure Q point, we measure value of base current ,collector current and collector voltage under dc conditions(no signal condition).



Find V_{CEQ} and I_{CQ}

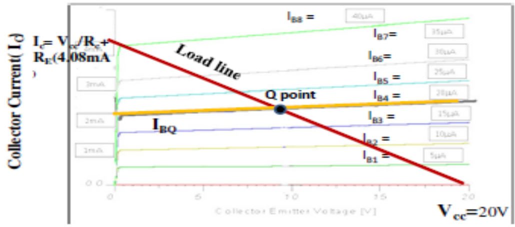


Collector current under no signal condition also known as dc bias current(Q point current)

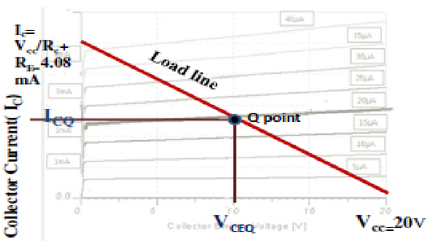
Collector to emitter voltage under no signal condition also known as dc bias voltage(Q point voltage)

Locate Q point

. Once we measure values of currents and voltage we can locate Q point by two methods
In the first method we fix output characteristics for IBQ(measured value) then draw load line(by joining V_{CC} and I_c) .Fix point as intersection of the two



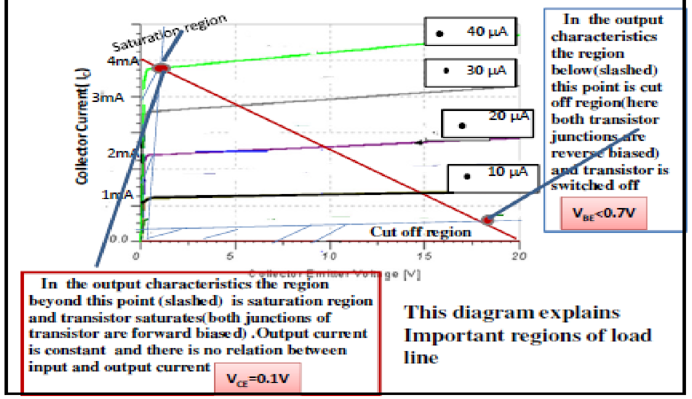
- In the second method we use V_{CEQ} and I_{CQ} values and load line as shown



Interpretation of Q point

- Once we locate Q point by any of the two methods ,we need to **interpret the location of Q point.**
- First we will study different regions of load line which will help us in interpretation of Q point.
- Remember load line is essential characteristics to locate and interpret Q point location.

- We need to find value of Qpoint using output characteristics and load line of the given amplifier circuit



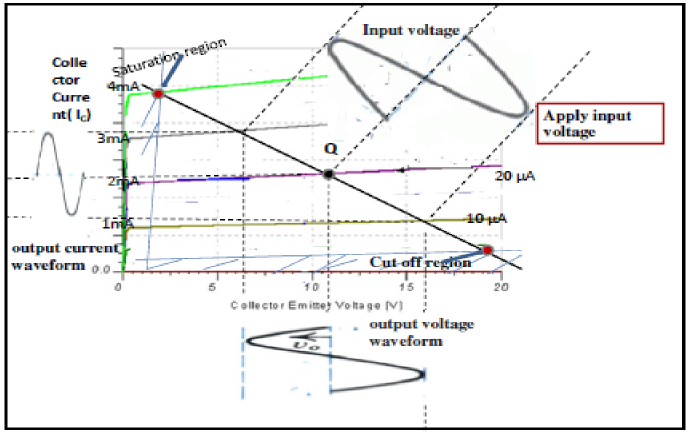
This diagram explains Important regions of load line

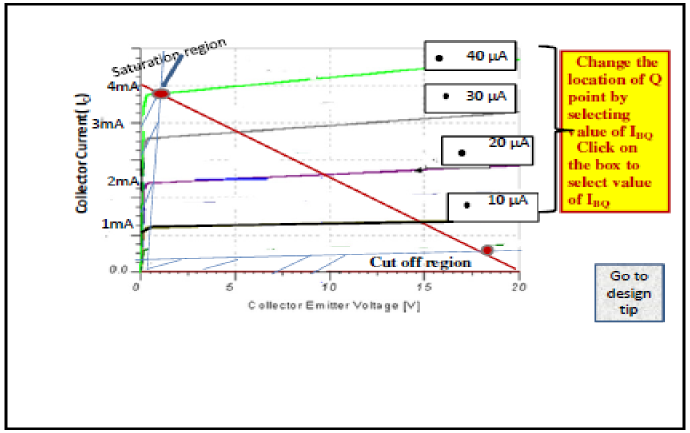
Interpretation of Q point(contd)

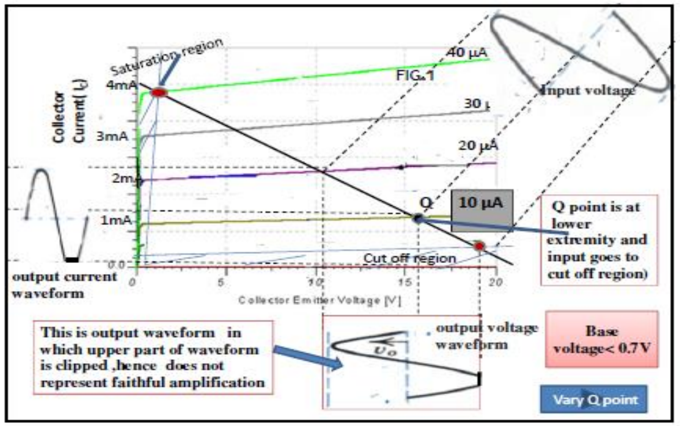
- In the process of interpretation of Q point
- Second important aspect is how to draw output waveforms for applied input voltage for given location of Q point.
- In the next slide Q point is already located and we will observe how can we draw output waveform?

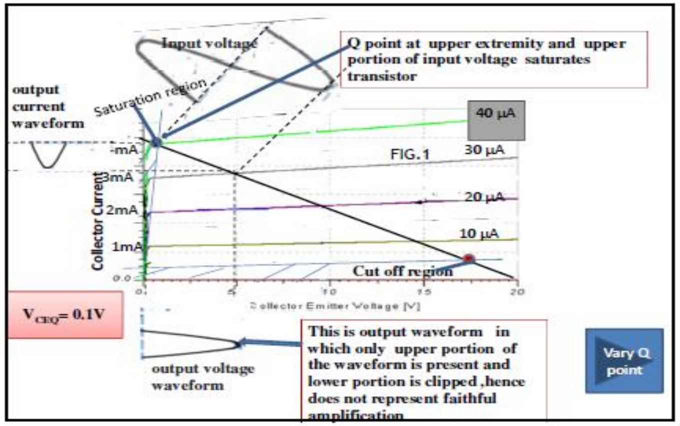
Why Q point location is important?

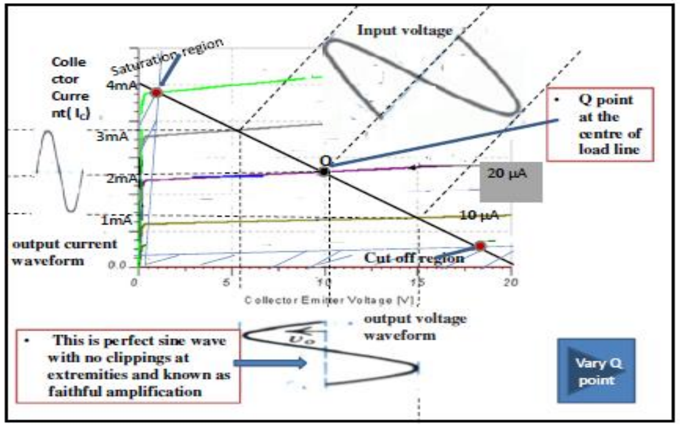
- If we change location of Q point will the shape of output waveform change?
- Let us vary location of Q point on the load line and observe the output waveform

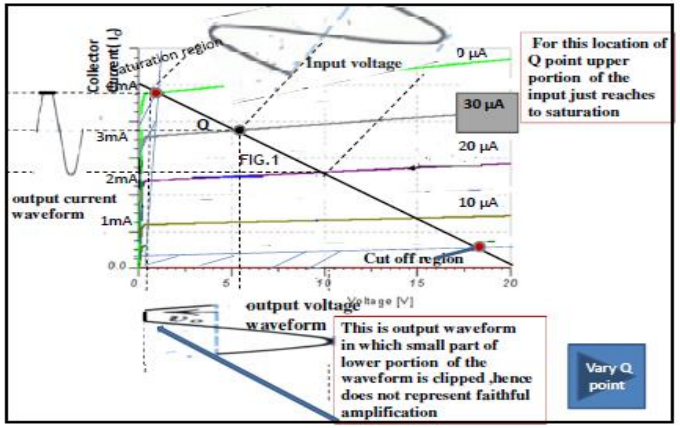





Saturation region
40 μA
FIG. 1
Input voltage
Collector Current(I_c)
4mA
3mA
30
20 μA
2mA
1mA
Q
10 μA
Q point is at lower extremity and input goes to cut off region)
Cut off region
output current waveform
Collector Emitter Voltage [V]
This is output waveform in which upper part of waveform is clipped ,hence does not represent faithful amplification
output voltage waveform
Base voltage< 0.7V
Vary Q point


Input voltage
Q point at upper extremity and upper portion of input voltage saturates transistor
output current waveform
Saturation region
40 μA
FIG. 1
30 μA
3mA
2mA
1mA
Collector Current
20 μA
10 μA
Cut off region
Collector Emitter Voltage [V]
V_{CEQ}= 0.1V
This is output waveform in which only upper portion of the waveform is present and lower portion is clipped ,hence does not represent faithful amplification
output voltage waveform
Vary Q point


Input voltage
Saturation region
Collector Current(I_C)
4mA
3mA
2mA
1mA
Q point at the centre of load line
Q
20 μA
10 μA
output current waveform
Cut off region
Collector Emitter Voltage [V]
This is perfect sine wave with no clippings at extremities and known as faithful amplification
output voltage waveform
Vary Q point


Collector Current(I_c)
Saturation region
Input voltage
For this location of Q point upper portion of the input just reaches to saturation
30 μA
Q
FIG. 1
3mA
20 μA
2mA
output current waveform
10 μA
1mA
Cut off region
output voltage waveform
This is output waveform in which small part of lower portion of the waveform is clipped ,hence does not represent faithful amplification
Vary Q point

Design tip1

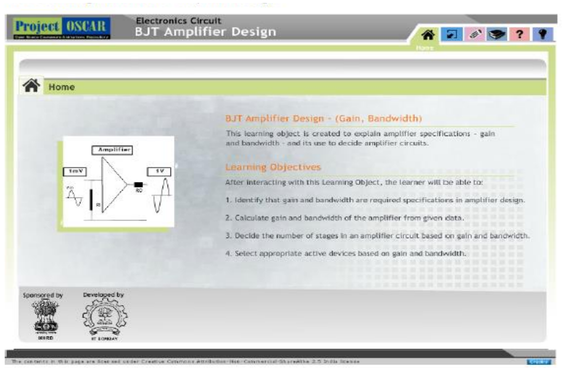
If Q point is located at the extremities then output waveforms are clipped at upper extremity or lower extremity.

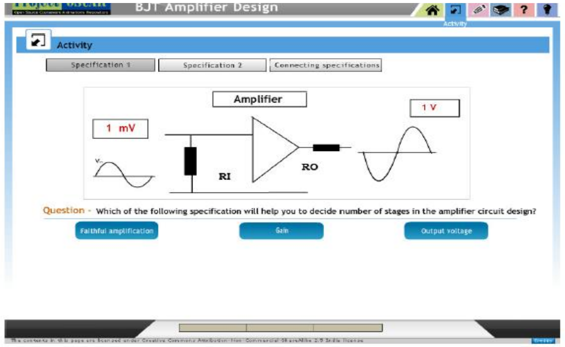
It is important to decide Q point location near centre to get faithful amplification

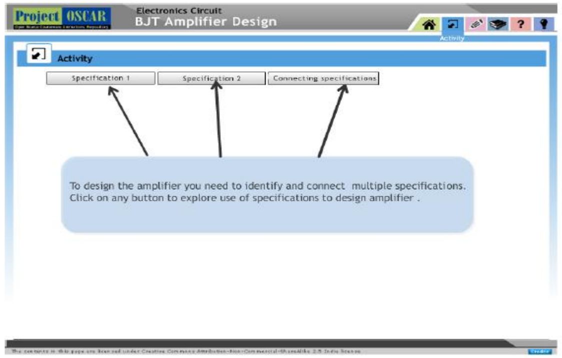
Practical value of $V_{CEQ=}$ Supply(V_{CC})/2(approx.)

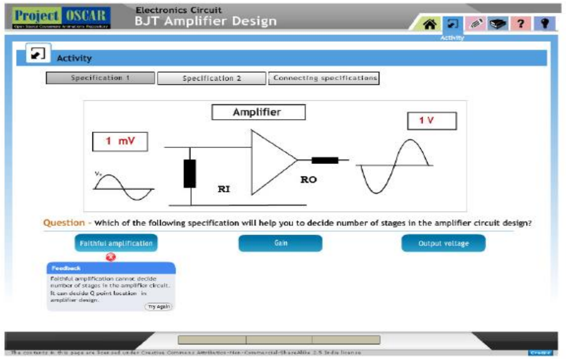
You can go back to find effect of Q point location

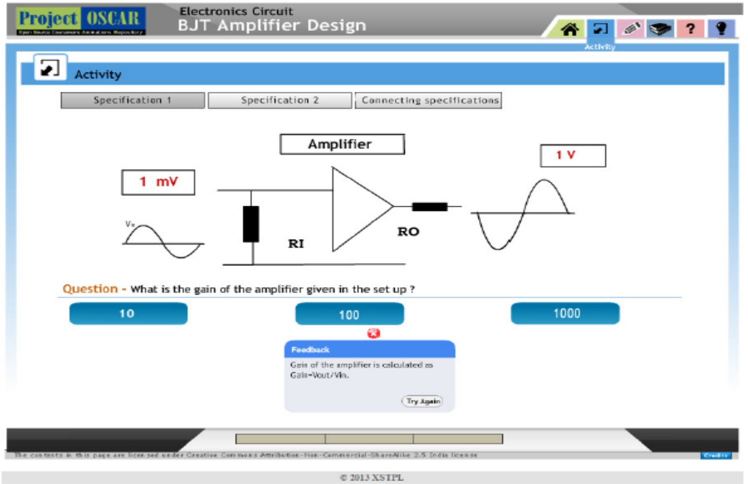
2.2. Modules 3 and 4 - Amplifier Design

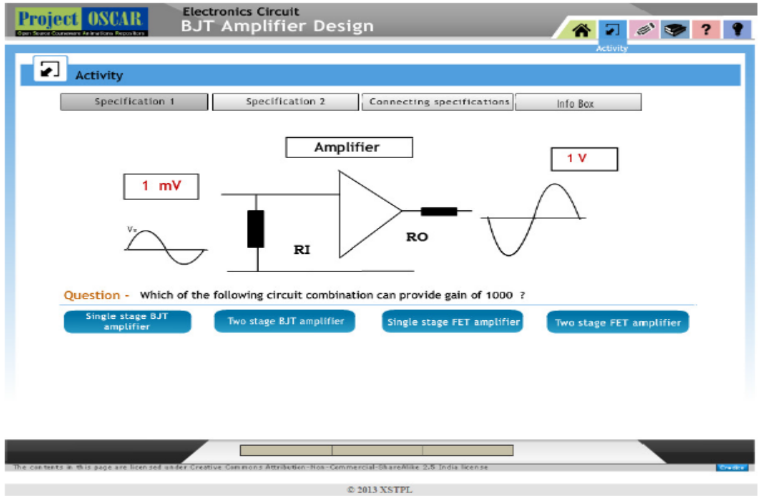


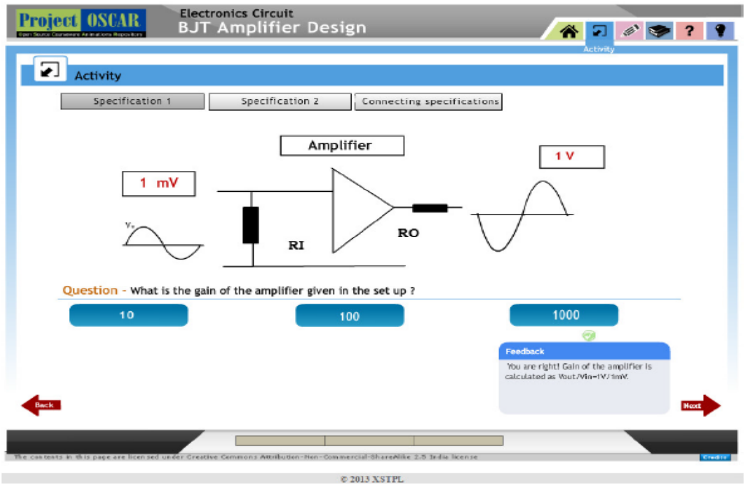


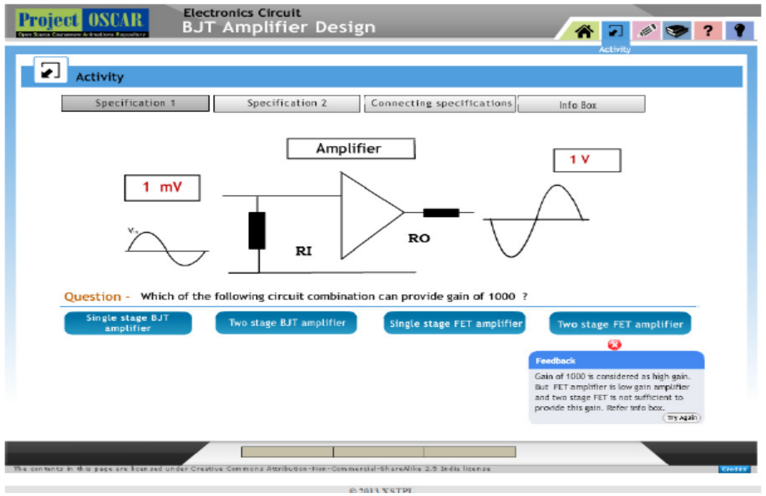


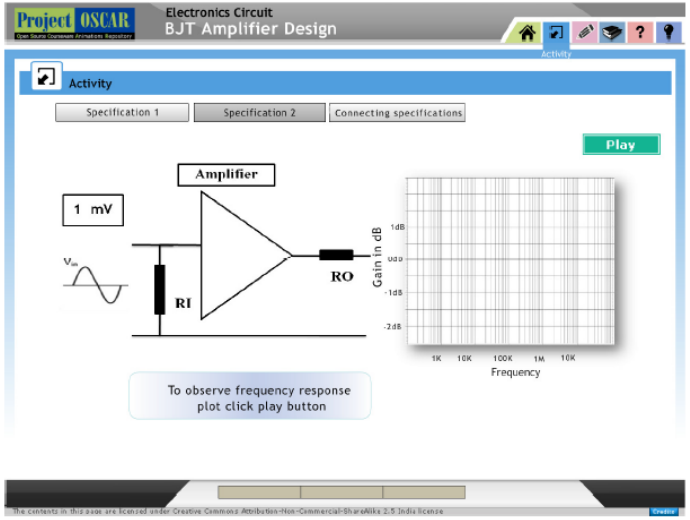


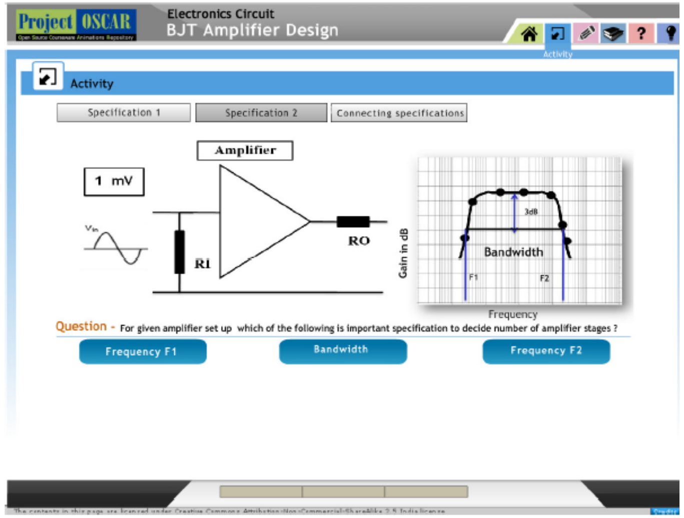

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Amplifier
1 mV
1 V
RI
RO
Question - What is the gain of the amplifier given in the set up ?
10
100
1000
Feedback
Gain of the amplifier is calculated as Gain=Vout/Vin.
Try Again
© 2013 XSTPL

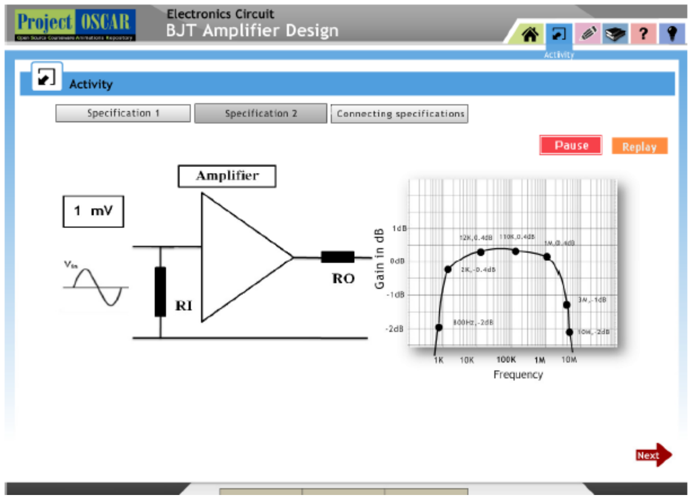

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Info Box
Amplifier
1 mV
1 V
RI
RO
Question - Which of the following circuit combination can provide gain of 1000 ?
Single stage BJT amplifier
Two stage BJT amplifier
Single stage FET amplifier
Two stage FET amplifier
© 2013 XSTPL

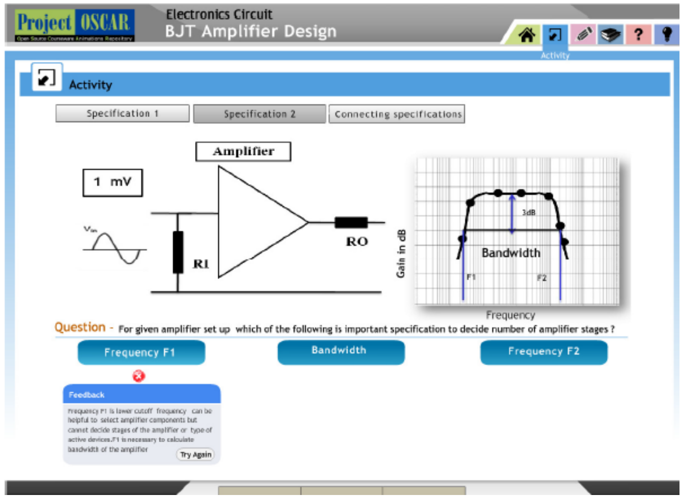

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Amplifier
1 mV
1 V
RI
RO
Question - What is the gain of the amplifier given in the set up ?
10
100
1000
Feedback
You are right! Gain of the amplifier is calculated as Vout/Vin=1V/1mV.
Back
Next
© 2013 XSTPL

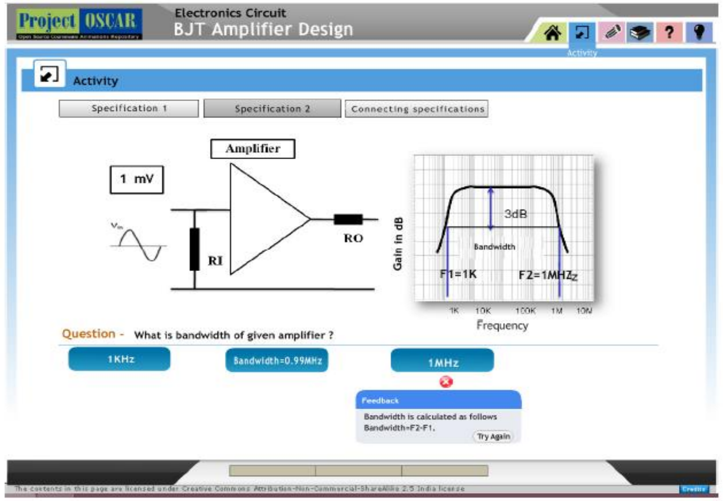

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Info Box
Amplifier
1 mV
1 V
RI
RO
Question - Which of the following circuit combination can provide gain of 1000 ?
Single stage BJT amplifier
Two stage BJT amplifier
Single stage FET amplifier
Two stage FET amplifier
Feedback
Gain of 1000 is considered as high gain. But FET amplifier is low gain amplifier and two stage FET is not sufficient to provide this gain. Refer info box.
Try Again

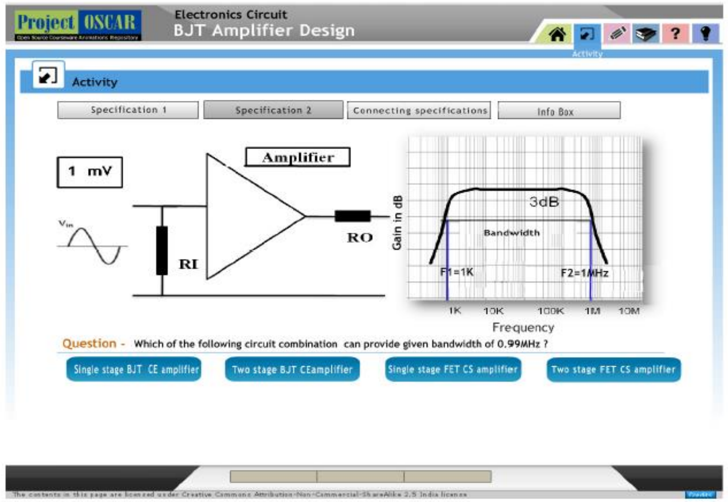

Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Play
Amplifier
1 mV
RI
RO
Gain in dB
Frequency
To observe frequency response plot click play button

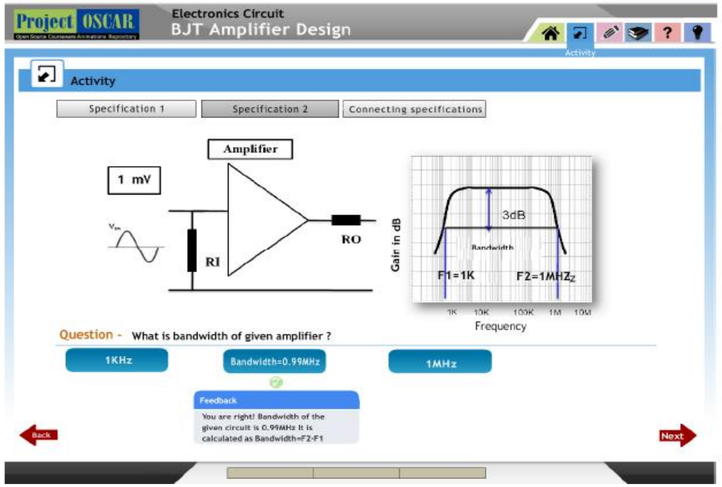

Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Amplifier
1 mV
RI
RO
Gain in dB
Bandwidth
Frequency
Question - For given amplifier set up which of the following is important specification to decide number of amplifier stages ?
Frequency F1
Bandwidth
Frequency F2

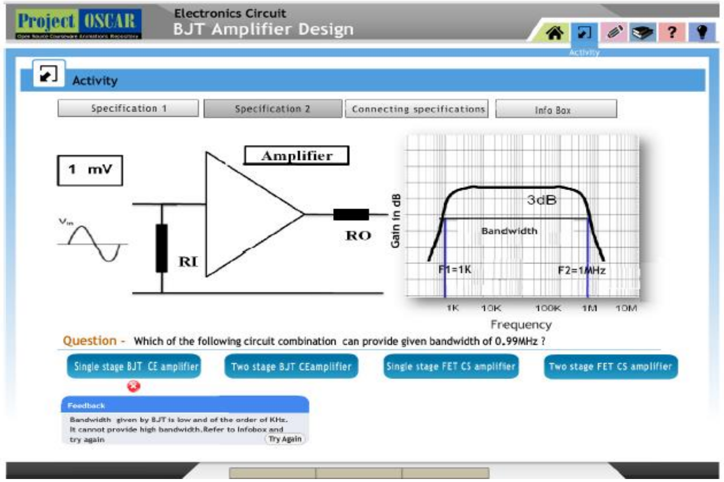

Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Pause
Replay
Amplifier
1 mV
RI
RO
Gain in dB
Frequency
Next

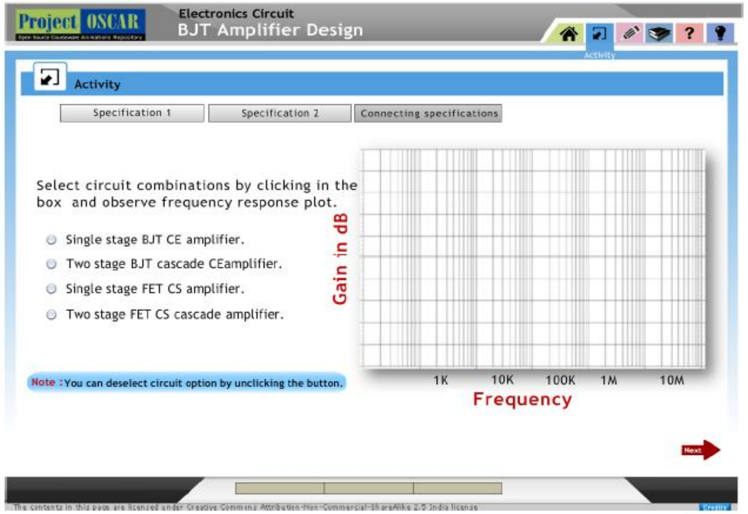

Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Amplifier
1 mV
RI
RO
Gain in dB
Bandwidth
Frequency
Question - For given amplifier set up which of the following is important specification to decide number of amplifier stages ?
Frequency F1
Bandwidth
Frequency F2
Feedback
Frequency F1 is lower cutoff frequency can be helpful to select amplifier components but cannot decide stages of the amplifier or type of active devices.F1 is necessary to calculate bandwidth of the amplifier
Try Again

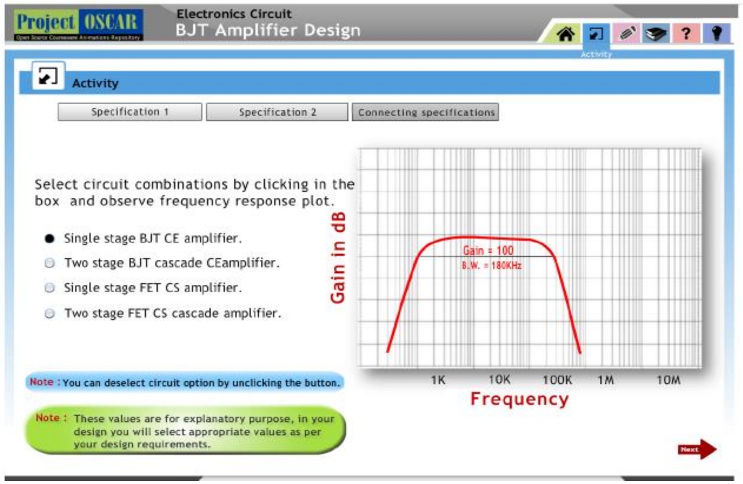

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Amplifier
1 mV
RI
RO
3dB
Bandwidth
F1=1K
F2=1MHZz
Gain in dB
Frequency
Question - What is bandwidth of given amplifier ?
1KHz
Bandwidth=0.99MHz
1MHz
Feedback
Bandwidth is calculated as follows
Bandwidth=F2-F1.
Try Again

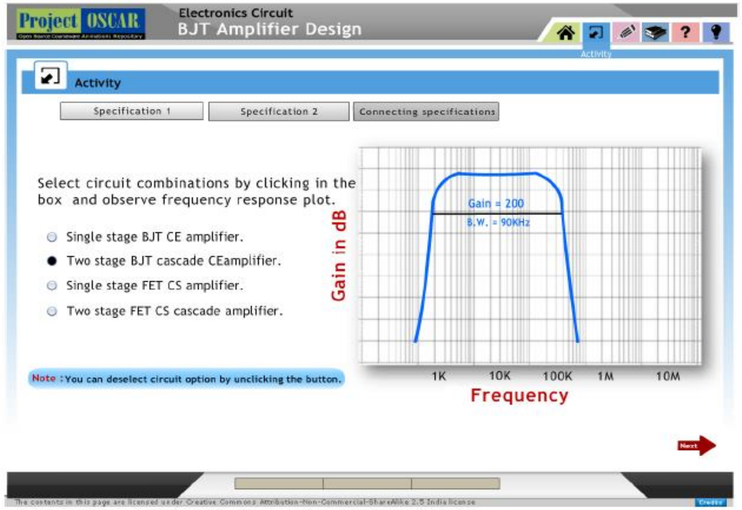

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Info Box
Amplifier
1 mV
RI
RO
3dB
Bandwidth
F1=1K
F2=1MHz
Gain in dB
Frequency
Question - Which of the following circuit combination can provide given bandwidth of 0.99MHz ?
Single stage BJT CE amplifier
Two stage BJT CEamplifier
Single stage FET CS amplifier
Two stage FET CS amplifier

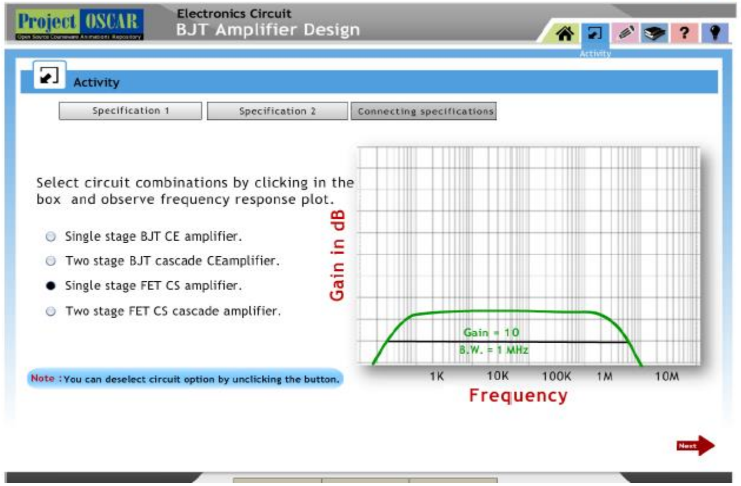

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Amplifier
1 mV
RI
RO
3dB
F1=1K
F2=1MHZz
Gain in dB
Frequency
Question - What is bandwidth of given amplifier ?
1KHz
Bandwidth=0.99MHz
1MHz
Feedback
You are right! Bandwidth of the given circuit is 0.99MHz It is calculated as Bandwidth=F2-F1
Back
Next

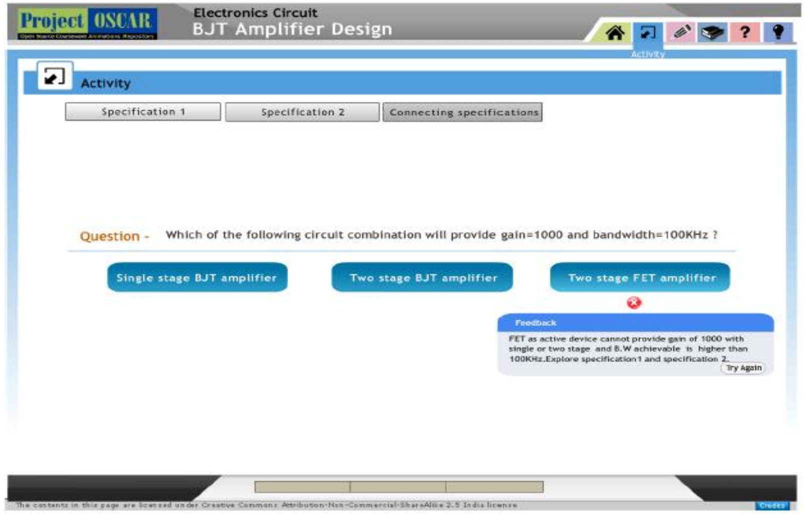

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Info Box
Amplifier
1 mV
RI
RO
3dB
Bandwidth
F1=1K
F2=1MHz
Gain in dB
Frequency
Question - Which of the following circuit combination can provide given bandwidth of 0.99MHz ?
Single stage BJT CE amplifier
Two stage BJT CEamplifier
Single stage FET CS amplifier
Two stage FET CS amplifier
Feedback
Try Again

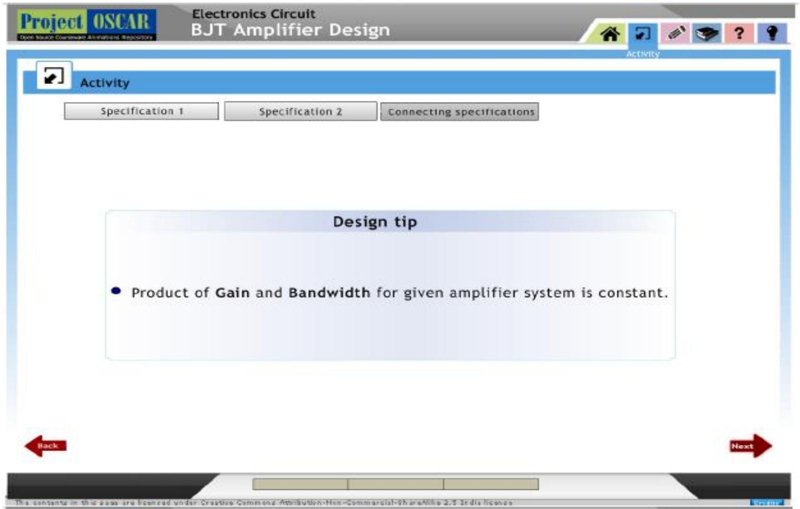

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Select circuit combinations by clicking in the box and observe frequency response plot.
Single stage BJT CE amplifier.
Two stage BJT cascade CEamplifier.
Single stage FET CS amplifier.
Two stage FET CS cascade amplifier.
Gain in dB
1K 10K 100K 1M 10M
Frequency
Note : You can deselect circuit option by unclicking the button.
Next

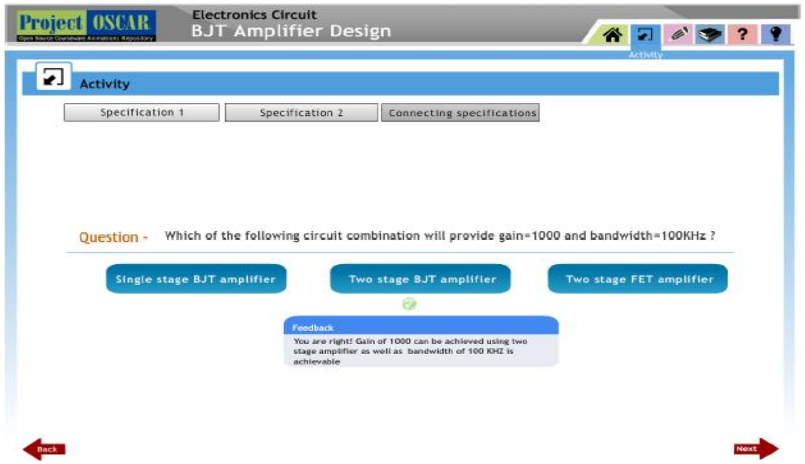

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Select circuit combinations by clicking in the box and observe frequency response plot.
Single stage BJT CE amplifier.
Two stage BJT cascade CEamplifier.
Single stage FET CS amplifier.
Two stage FET CS cascade amplifier.
Gain in dB
Gain = 100
B.W. = 180KHz
1K 10K 100K 1M 10M
Frequency
Note : You can deselect circuit option by unclicking the button.
Note : These values are for explanatory purpose, in your design you will select appropriate values as per your design requirements.
Next

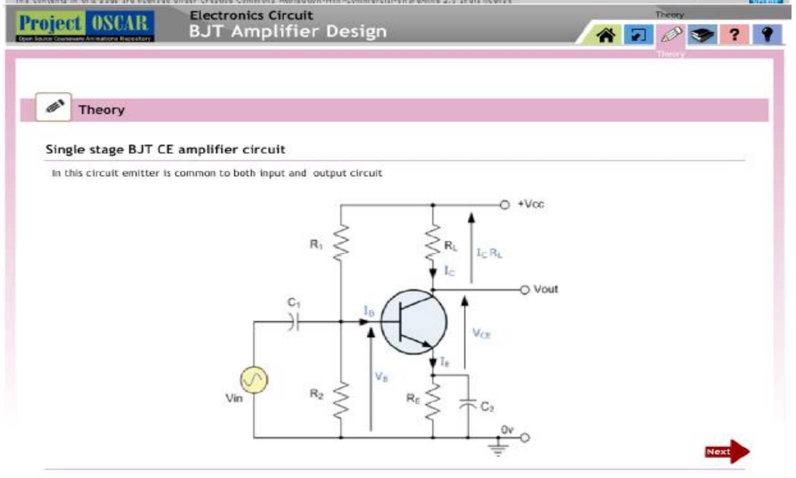

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Select circuit combinations by clicking in the box and observe frequency response plot.
Single stage BJT CE amplifier.
Two stage BJT cascade CEamplifier.
Single stage FET CS amplifier.
Two stage FET CS cascade amplifier.
Gain in dB
Gain = 200
B.W. = 90KHz
1K 10K 100K 1M 10M
Frequency
Note : You can deselect circuit option by unclicking the button.
Next


Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Select circuit combinations by clicking in the box and observe frequency response plot.
Single stage BJT CE amplifier.
Two stage BJT cascade CEamplifier.
Single stage FET CS amplifier.
Two stage FET CS cascade amplifier.
Gain in dB
Gain = 10
B.W. = 1 MHz
1K 10K 100K 1M 10M
Frequency
Note : You can deselect circuit option by unclicking the button.
Next

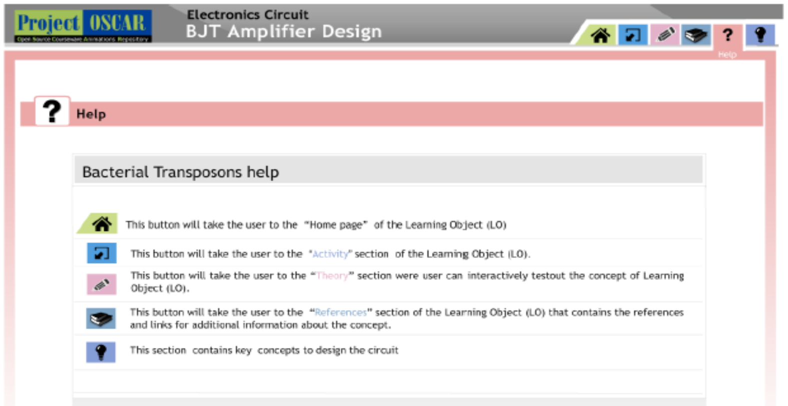

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Question - Which of the following circuit combination will provide gain=1000 and bandwidth=100KHz ?
Single stage BJT amplifier
Two stage BJT amplifier
Two stage FET amplifier
Feedback
FET as active device cannot provide gain of 1000 with single or two stage and B.W achievable is higher than 100KHz.Explore specification1 and specification 2.
Try Again

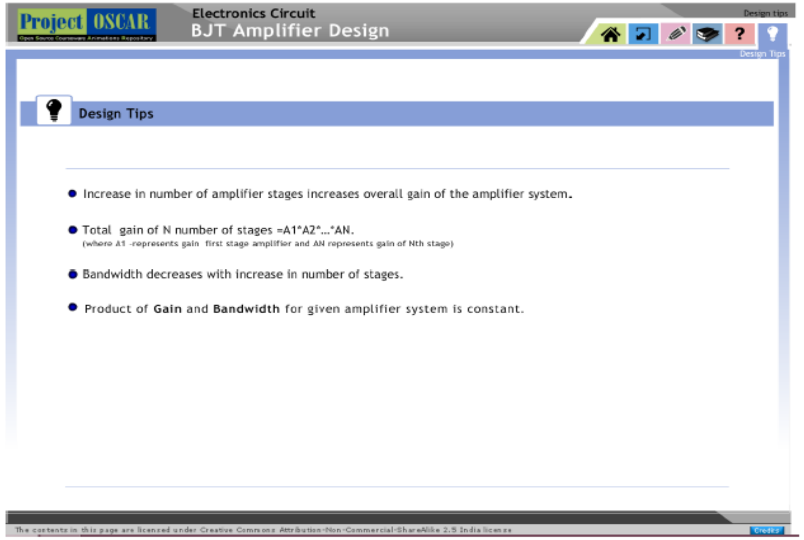

Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Design tip
Product of Gain and Bandwidth for given amplifier system is constant.
Back
Next


Project OSCAR
Electronics Circuit
BJT Amplifier Design
Activity
Specification 1
Specification 2
Connecting specifications
Question - Which of the following circuit combination will provide gain=1000 and bandwidth=100KHz ?
Single stage BJT amplifier
Two stage BJT amplifier
Two stage FET amplifier
Feedback
You are right! Gain of 1000 can be achieved using two stage amplifier as well as bandwidth of 100 KHZ is achievable
Back
Next


Project OSCAR
Electronics Circuit
BJT Amplifier Design
Theory
Single stage BJT CE amplifier circuit
In this circuit emitter is common to both input and output circuit
+Vcc
R1
RL
IC RL
IC
Vout
C1
IB
VCE
IE
VB
Vin
R2
RE
C2
0v
Next


Project OSCAR
Open Source Courseware Animations Repository
Electronics Circuit
BJT Amplifier Design
References
References
Books for further reading
Books:
1) Electronics Devices and Circuits—David Bell
2) Electronics circuit analysis and design-William Hayt,Gerold Neudeck
Credits


Project OSCAR
Open Source Courseware Animations Repository
Electronics Circuit
BJT Amplifier Design
Help
Help
Bacterial Transposons help
This button will take the user to the "Home page" of the Learning Object (LO)
This button will take the user to the "Activity" section of the Learning Object (LO).
This button will take the user to the "Theory" section were user can interactively testout the concept of Learning Object (LO).
This button will take the user to the "References" section of the Learning Object (LO) that contains the references and links for additional information about the concept.
This section contains key concepts to design the circuit


Project OSCAR
Open Source Courseware Animations Repository
Electronics Circuit
BJT Amplifier Design
Design tips
Design Tips
Design Tips
Increase in number of amplifier stages increases overall gain of the amplifier system.
Total gain of N number of stages =A1*A2*...*AN.
(where A1 -represents gain first stage amplifier and AN represents gain of Nth stage)
Bandwidth decreases with increase in number of stages.
Product of Gain and Bandwidth for given amplifier system is constant.
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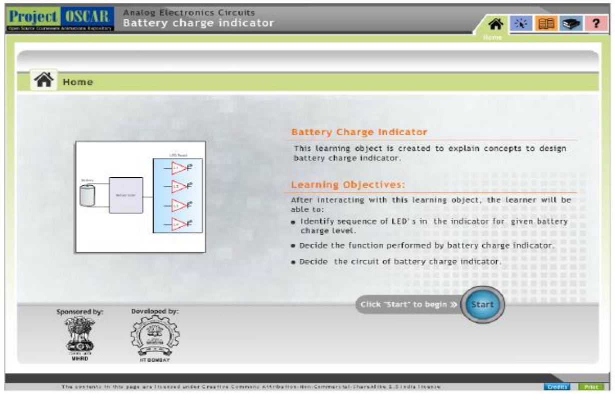
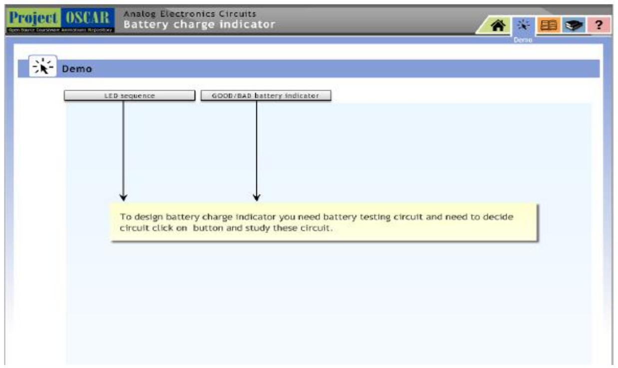
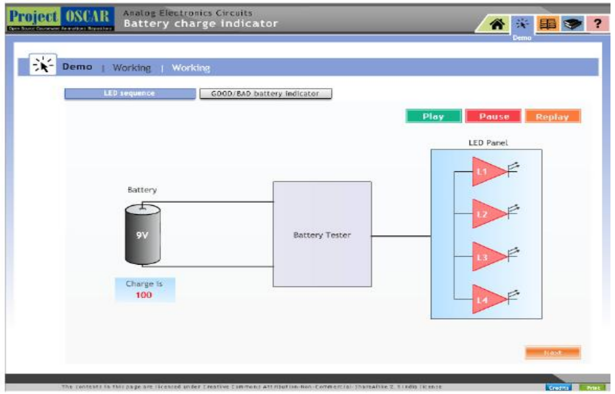
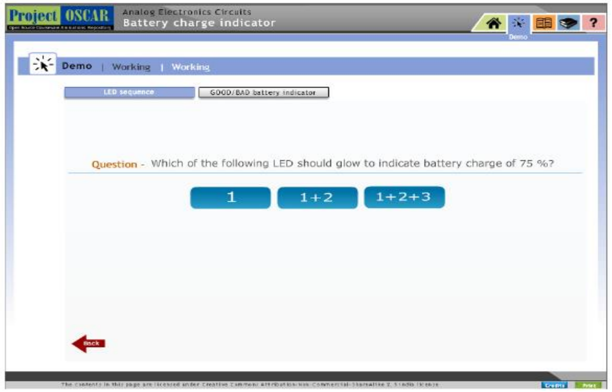
Credits

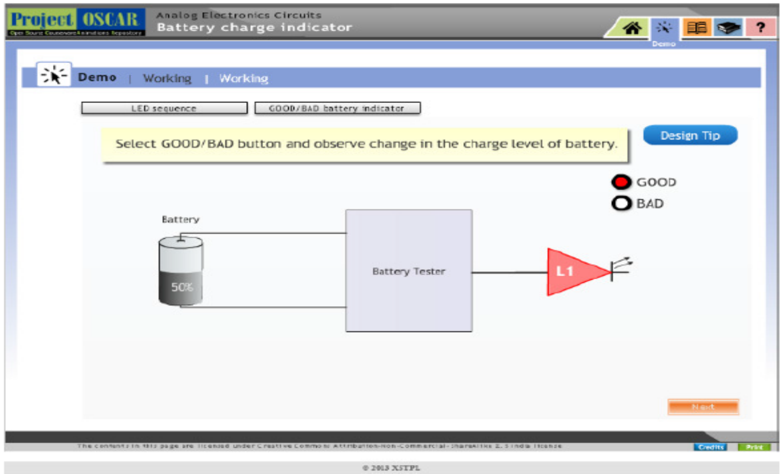
2.3. Modules 5 and 6 - OP-AMP comparator design

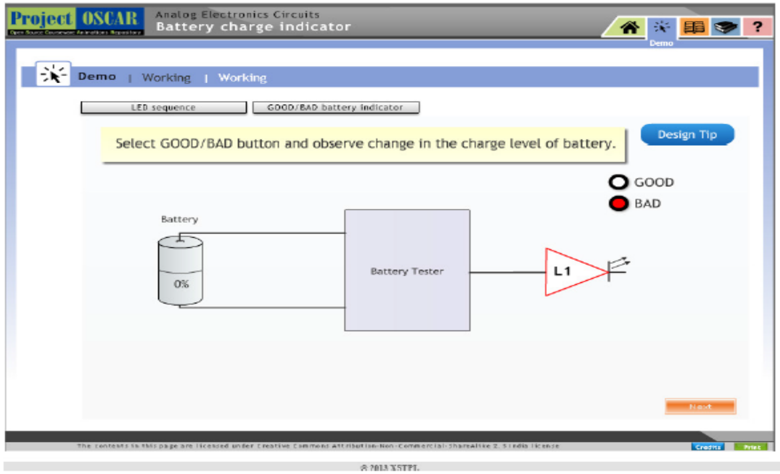


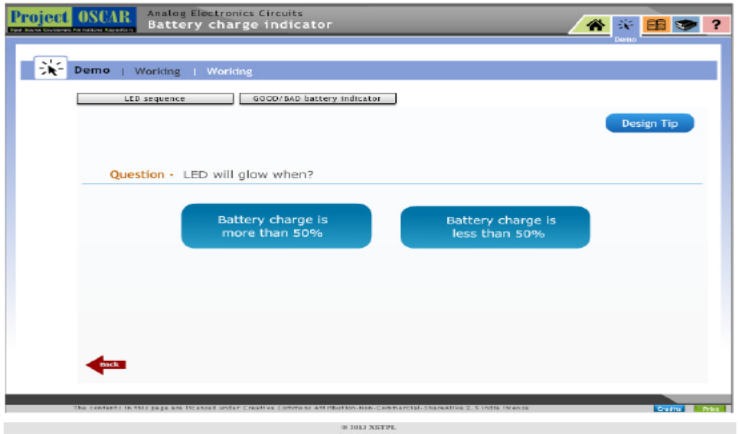




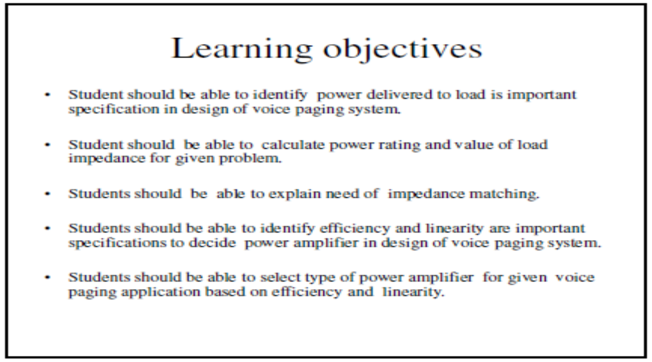


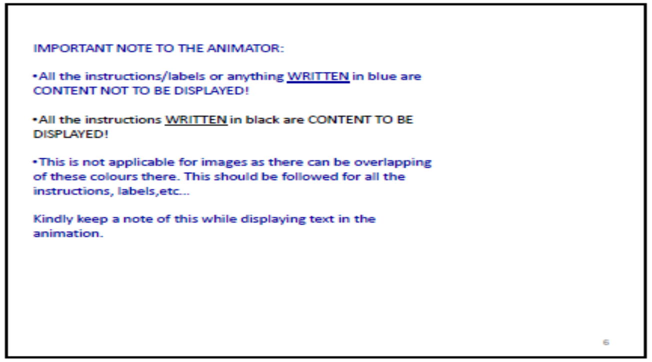

Project OSCAR
Analog Electronics Circuits
Battery charge indicator
Demo | Working | Working
LED sequence
GOOD/BAD battery indicator
Select GOOD/BAD button and observe change in the charge level of battery.
Design Tip
GOOD
BAD
Battery
50%
Battery Tester
L1

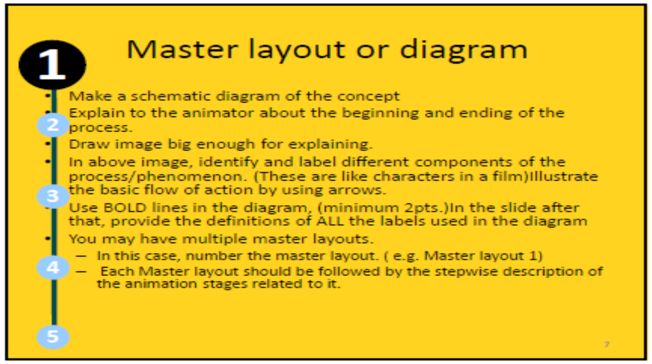

Project OSCAR
Analog Electronics Circuits
Battery charge indicator
Demo | Working | Working
LED sequence
GOOD/BAD battery indicator
Select GOOD/BAD button and observe change in the charge level of battery.
Design Tip
GOOD
BAD
Battery
0%
Battery Tester
L1

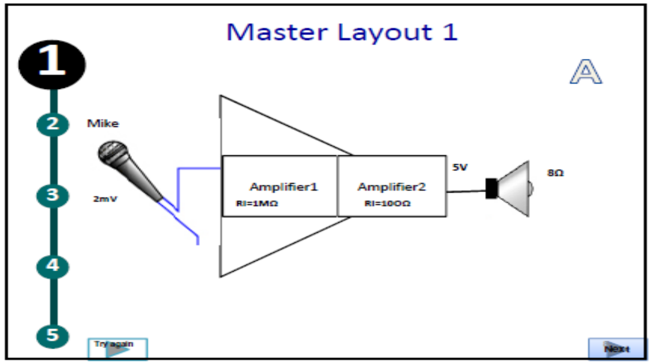

Project OSCAR
Analog Electronics Circuits
Battery charge indicator
Demo | Working | Working
LED sequence
GOOD/BAD battery indicator
Design Tip
Question - LED will glow when?
Battery charge is more than 50%
Battery charge is less than 50%

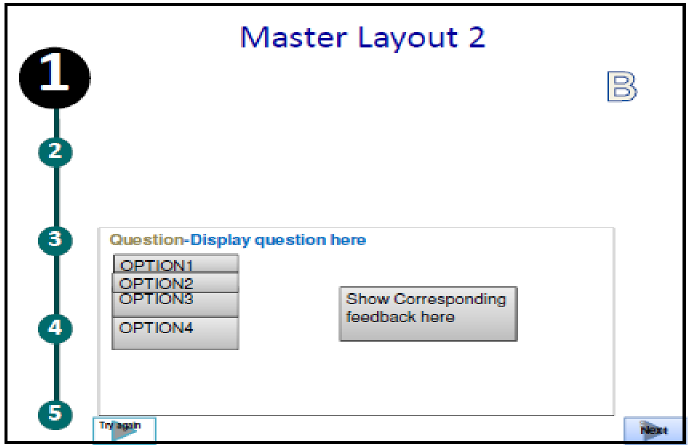
2.4. Modules 7 and 8 - Power amplifier design (Instructional Design Document-IDD)

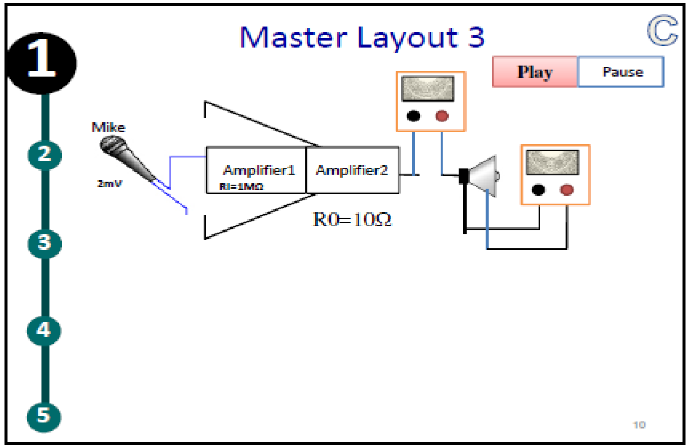


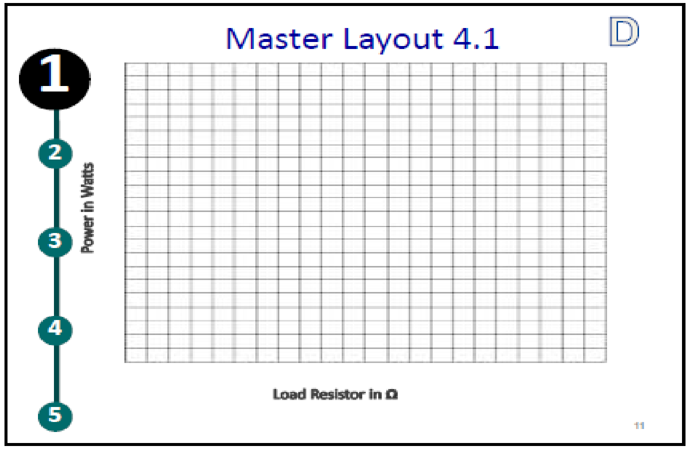


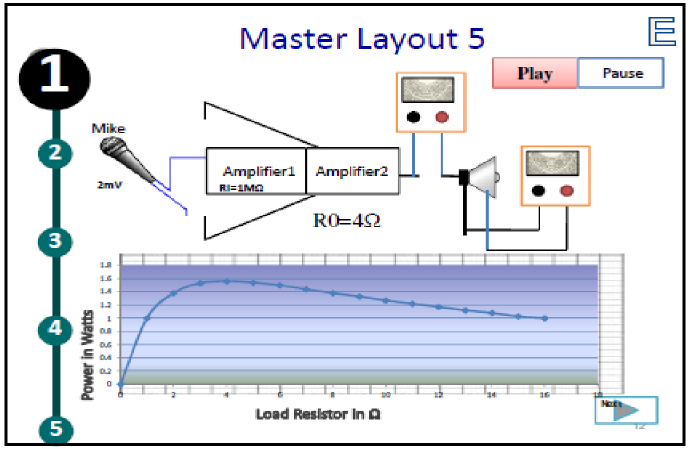





Master Layout 2
B
1
2
3
4
5
Question-Display question here
OPTION1
OPTION2
OPTION3
OPTION4
Show Corresponding feedback here
Try again
Next


Master Layout 3
C
Play
Pause
Mike
2mV
Amplifier1
Amplifier2
R0=10Ω
1
2
3
4
5

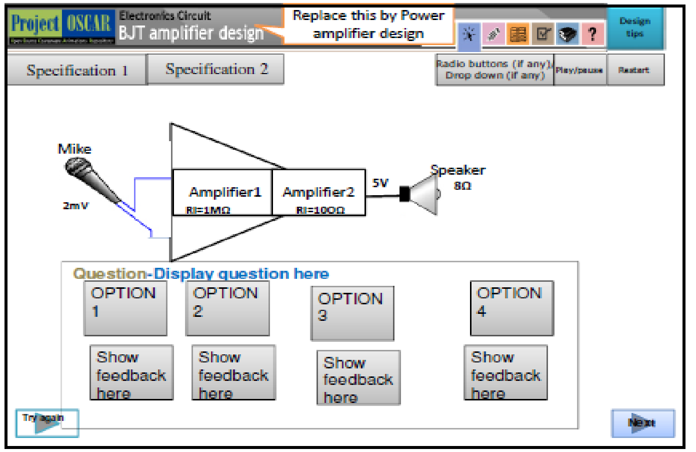

Master Layout 4.1
D
Power in Watts
Load Resistor in Ω
1
2
3
4
5


Master Layout 5
E
Play
Pause
Mike
2mV
Amplifier1
Amplifier2
R0=4Ω
Power in Watts
Load Resistor in Ω
1
2
3
4
5

Animation design

- Please see the design template provided in the next slide.
- This is a sample template, and you are free to change as per your design requirements.
- Try and recreate the sections/subsections as shown in the template.

13



Stepwise description of process

- The goal of the document is to provide instructions to an animator who is not a expert.
- You have to describe what steps the animator should take to make your concept come alive as a moving visualization.
- Use one slide per step. This will ensure clarity of the explanation.
- Add a image of the step in the box, and the details in the table below the box.
- You can use any images for reference, but mention about it's copyright status
- The animator will have to re-draw / re-create the drawings

- *Add more slides as per the requirement of the animation*

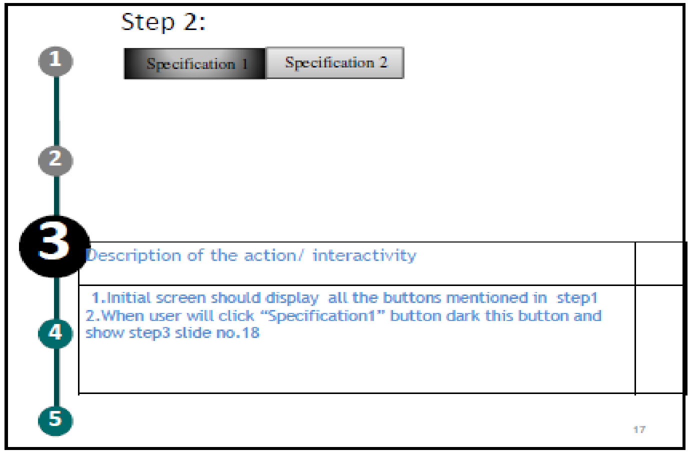
15

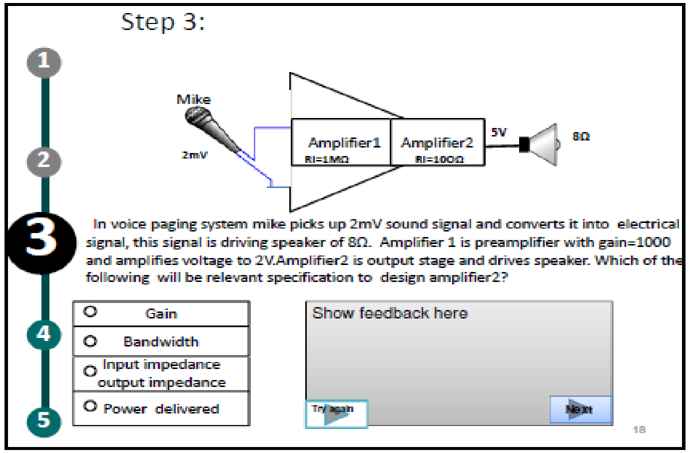
Step 1:

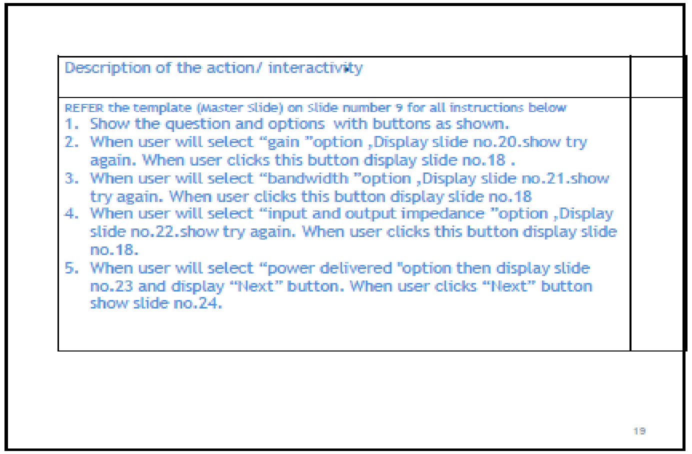
Specification 1 | Specification 2

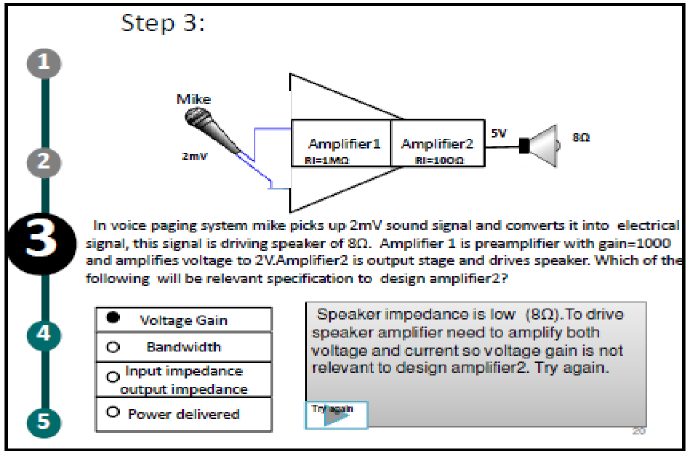
Description of the action/ interactivity	
1.Show 2 clickable buttons as shown in this slide .show corresponding texts like specification1, specification2 2.Initial screen should display both buttons. But allow user to click first button only	

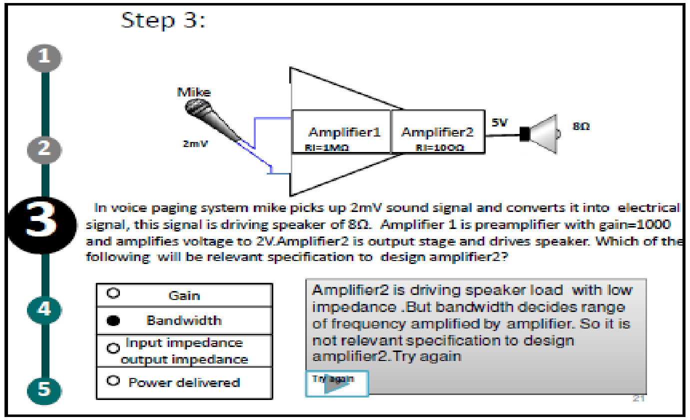
16

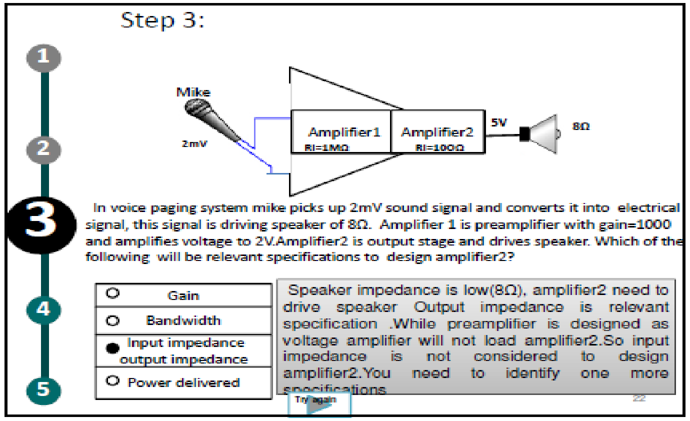

Step 2:
Specification 1
Specification 2
1
2
3
4
5
Description of the action/ interactivity
1.Initial screen should display all the buttons mentioned in step1
2.When user will click "Specification1" button dark this button and show step3 slide no.18
17

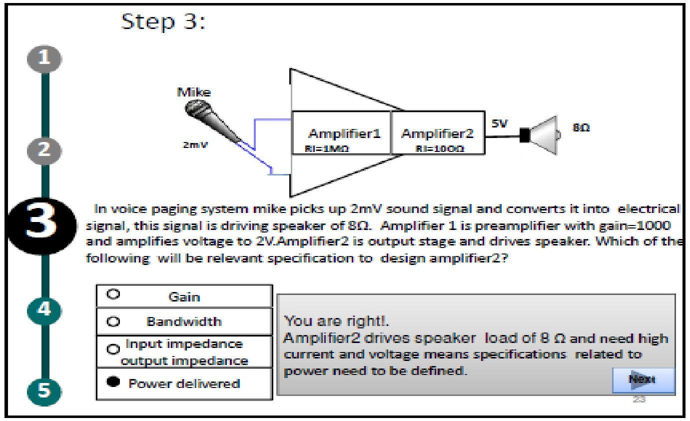

Step 3:
1
2
3
4
5
Mike
2mV
Amplifier1
Rl=1MΩ
Amplifier2
Rl=100Ω
5V
8Ω
In voice paging system mike picks up 2mV sound signal and converts it into electrical signal, this signal is driving speaker of 8Ω. Amplifier 1 is preamplifier with gain=1000 and amplifies voltage to 2V.Amplifier2 is output stage and drives speaker. Which of the following will be relevant specification to design amplifier2?
Gain
Bandwidth
Input impedance output impedance
Power delivered
Show feedback here
Try again
Next
18

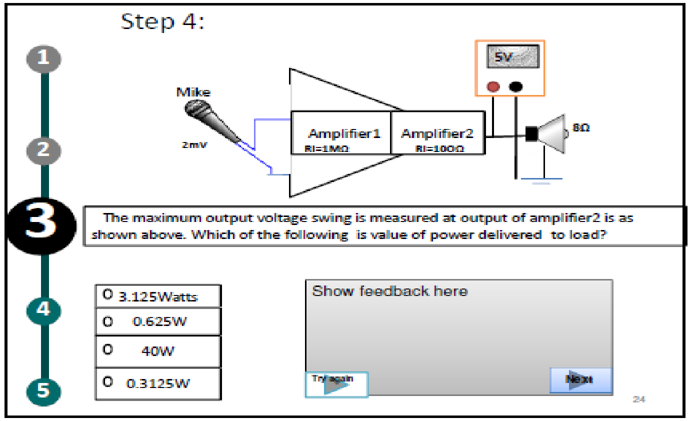

Description of the action/ interactivity
REFER the template (Master Slide) on Slide number 9 for all instructions below
1. Show the question and options with buttons as shown.
2. When user will select "gain "option ,Display slide no.20.show try again. When user clicks this button display slide no.18 .
3. When user will select "bandwidth "option ,Display slide no.21.show try again. When user clicks this button display slide no.18
4. When user will select "input and output impedance "option ,Display slide no.22.show try again. When user clicks this button display slide no.18.
5. When user will select "power delivered "option then display slide no.23 and display "Next" button. When user clicks "Next" button show slide no.24.
19

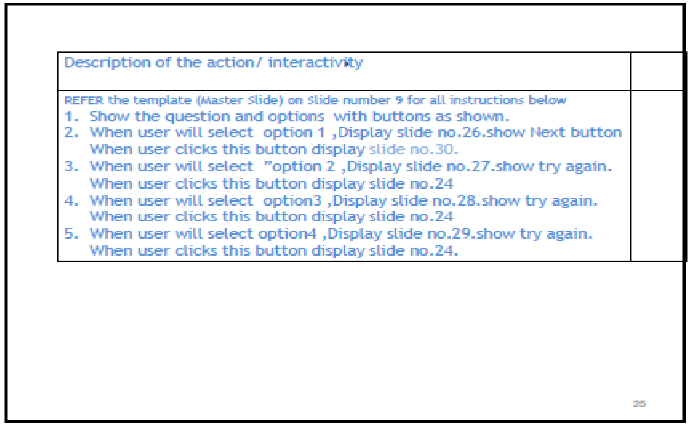

Step 3:
1
2
3
4
5
Mike
2mV
Amplifier1
Rl=1MΩ
Amplifier2
Rl=100Ω
5V
8Ω
In voice paging system mike picks up 2mV sound signal and converts it into electrical signal, this signal is driving speaker of 8Ω. Amplifier 1 is preamplifier with gain=1000 and amplifies voltage to 2V.Amplifier2 is output stage and drives speaker. Which of the following will be relevant specification to design amplifier2?
Voltage Gain
Bandwidth
Input impedance output impedance
Power delivered
Speaker impedance is low (8Ω).To drive speaker amplifier need to amplify both voltage and current so voltage gain is not relevant to design amplifier2. Try again.
Try again
20


Step 3:
Mike
2mV
Amplifier1
Rl=1MΩ
Amplifier2
Rl=100Ω
5V
8Ω
In voice paging system mike picks up 2mV sound signal and converts it into electrical signal, this signal is driving speaker of 8Ω. Amplifier 1 is preamplifier with gain=1000 and amplifies voltage to 2V.Amplifier2 is output stage and drives speaker. Which of the following will be relevant specification to design amplifier2?
Gain
Bandwidth
Input impedance output impedance
Power delivered
Amplifier2 is driving speaker load with low impedance .But bandwidth decides range of frequency amplified by amplifier. So it is not relevant specification to design amplifier2.Try again
Try again
21


Step 3:
Mike
2mV
Amplifier1
Rl=1MΩ
Amplifier2
Rl=100Ω
5V
8Ω
In voice paging system mike picks up 2mV sound signal and converts it into electrical signal, this signal is driving speaker of 8Ω. Amplifier 1 is preamplifier with gain=1000 and amplifies voltage to 2V.Amplifier2 is output stage and drives speaker. Which of the following will be relevant specifications to design amplifier2?
Gain
Bandwidth
Input impedance output impedance
Power delivered
Speaker impedance is low(8Ω), amplifier2 need to drive speaker Output impedance is relevant specification .While preamplifier is designed as voltage amplifier will not load amplifier2.So input impedance is not considered to design amplifier2.You need to identify one more specifications
Try again
22

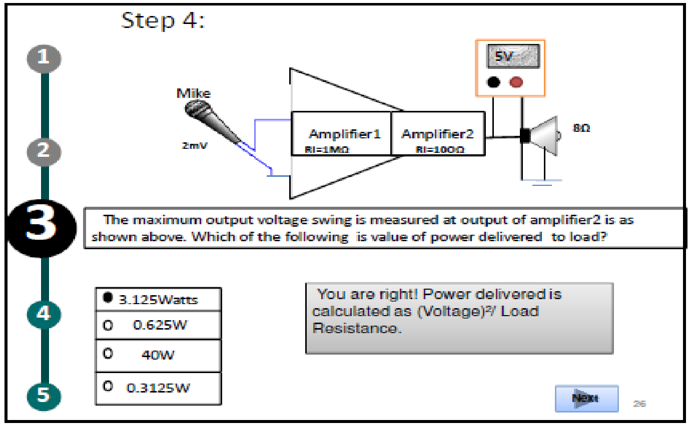

Step 3:
Mike
2mV
Amplifier1
Rl=1MΩ
Amplifier2
Rl=100Ω
5V
8Ω
In voice paging system mike picks up 2mV sound signal and converts it into electrical signal, this signal is driving speaker of 8Ω. Amplifier 1 is preamplifier with gain=1000 and amplifies voltage to 2V.Amplifier2 is output stage and drives speaker. Which of the following will be relevant specification to design amplifier2?
Gain
Bandwidth
Input impedance output impedance
Power delivered
You are right!.
Amplifier2 drives speaker load of 8 Ω and need high current and voltage means specifications related to power need to be defined.
Next
23

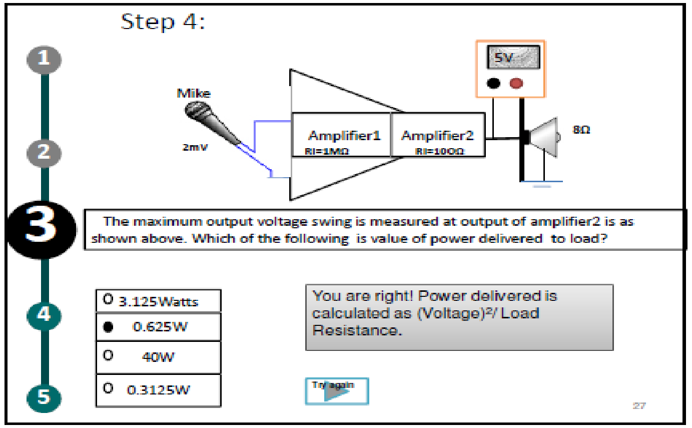

Step 4:
5V
Mike
2mV
Amplifier1
Rl=1MΩ
Amplifier2
Rl=100Ω
8Ω
The maximum output voltage swing is measured at output of amplifier2 is as shown above. Which of the following is value of power delivered to load?
3.125Watts
0.625W
40W
0.3125W
Show feedback here
Try again
Next
24

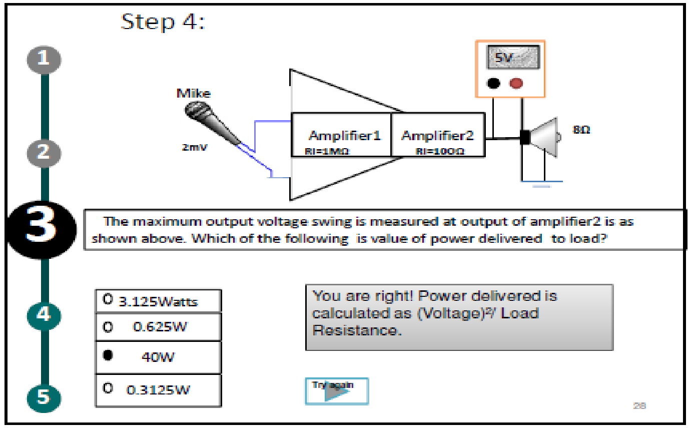


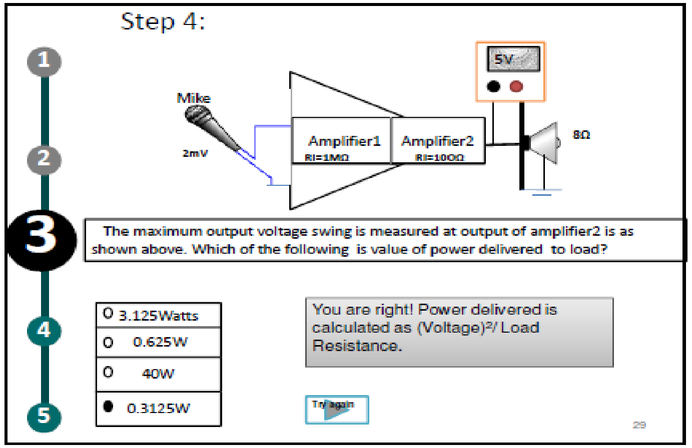
Description of the action/ interactivity	
REFER the template (Master Slide) on Slide number 9 for all instructions below 1. Show the question and options with buttons as shown. 2. When user will select option 1 ,Display slide no.26.show Next button When user clicks this button display slide no.30. 3. When user will select "option 2 ,Display slide no.27.show try again. When user clicks this button display slide no.24 4. When user will select option3 ,Display slide no.28.show try again. When user clicks this button display slide no.24 5. When user will select option4 ,Display slide no.29.show try again. When user clicks this button display slide no.24.	

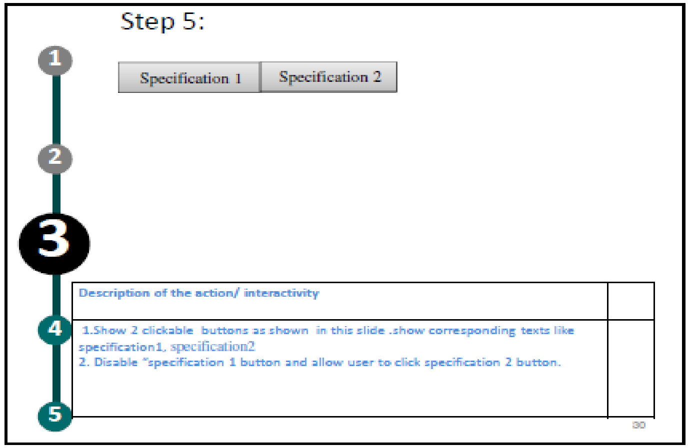
25

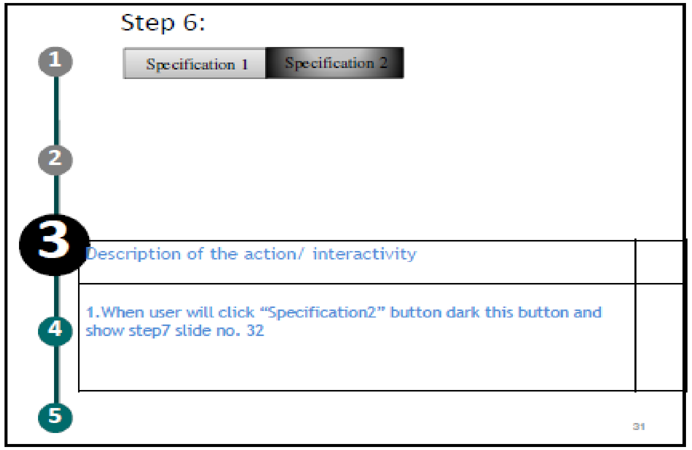


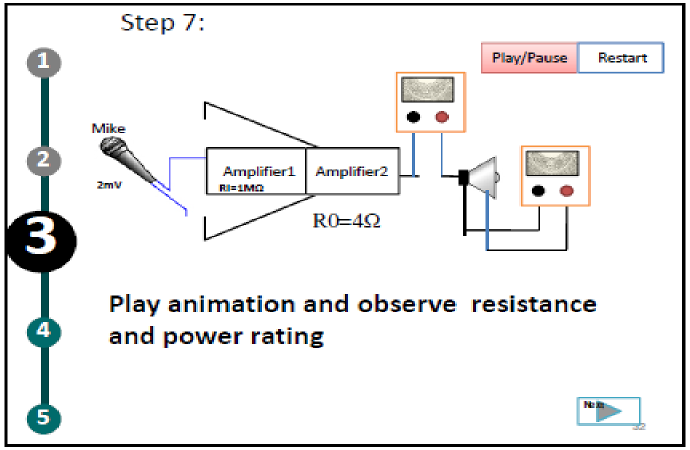





Step 4:
1
2
3
4
5
Mike
2mV
Amplifier1
Rl=1MΩ
Amplifier2
Rl=100Ω
5V
8Ω
The maximum output voltage swing is measured at output of amplifier2 is as shown above. Which of the following is value of power delivered to load?
3.125Watts
0.625W
40W
0.3125W
You are right! Power delivered is calculated as (Voltage)²/ Load Resistance.
29


Step 5:
1
2
3
4
5
Specification 1
Specification 2
Description of the action/ interactivity
1.Show 2 clickable buttons as shown in this slide .show corresponding texts like specification1, specification2
2. Disable "specification 1 button and allow user to click specification 2 button.
30


Step 6:
1
2
3
4
5
Specification 1
Specification 2
Description of the action/ interactivity
1.When user will click "Specification2" button dark this button and show step7 slide no. 32
31


Step 7:
1
2
3
4
5
Play/Pause
Restart
Mike
2mV
Amplifier1
Rl=1MΩ
Amplifier2
R0=4Ω
Play animation and observe resistance and power rating

Description of the action/ interactivity

When user clicks play button then show step 8to 15 (low speed of animation),slide no 34 Show black dots one by one as numbered (not to show numbers) as per values given in Table beside.

Use power values on Y axis After all dots are shown join these dots as shown above with thin black line as shown.

Show pause button while graph is plotted . And make it clickable. If user clicks "Pause button then stop plotting dots.

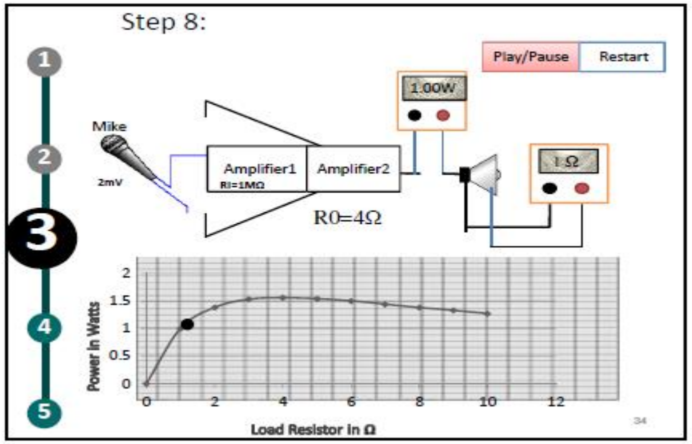
Show "Restart button "When user clicks "Restart button remove all dots and start plotting from initial dot.

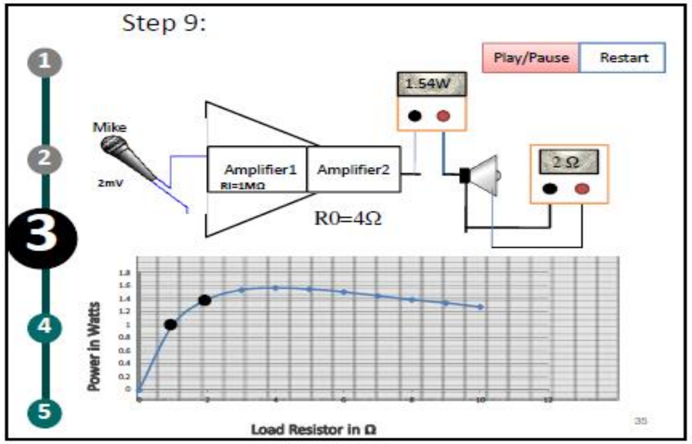
Always display Next button. When user clicks Next button show slide 34.

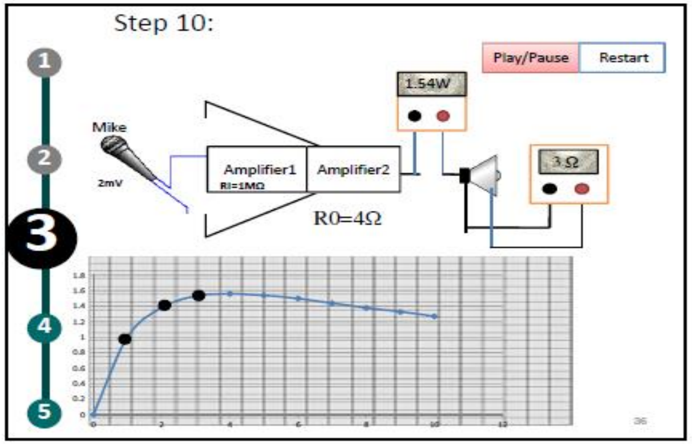
Table

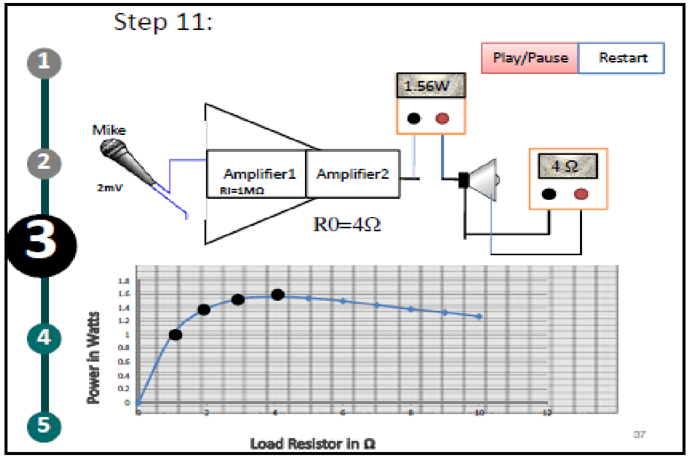
Load Resistance	power
0	0
1	1
2	1.38
3	1.53
4	1.56
5	1.54
6	1.5
7	1.44
8	1.38
9	1.33
10	1.27

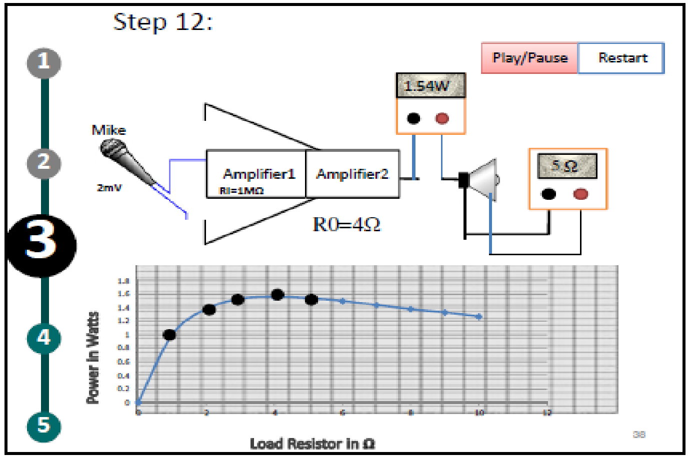
33

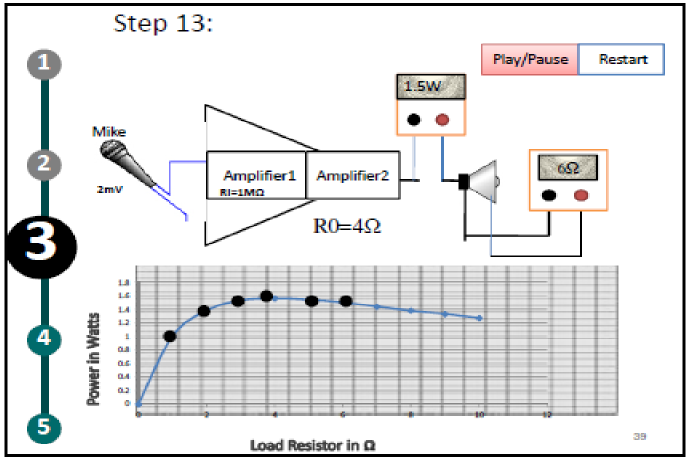


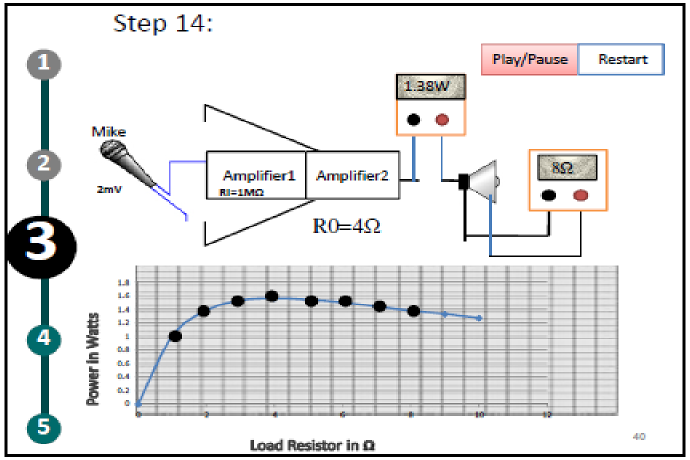


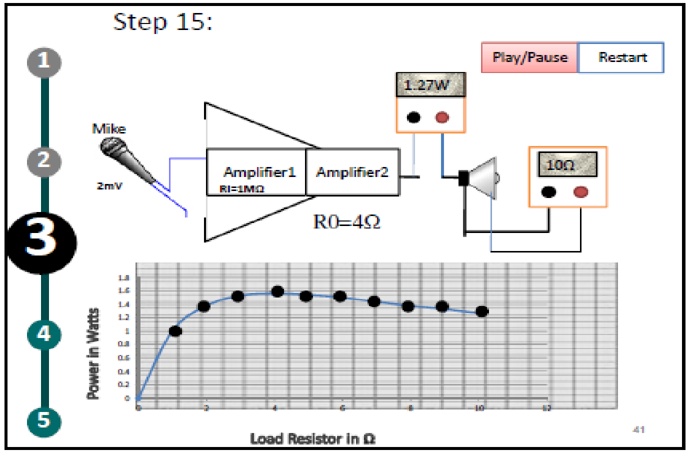


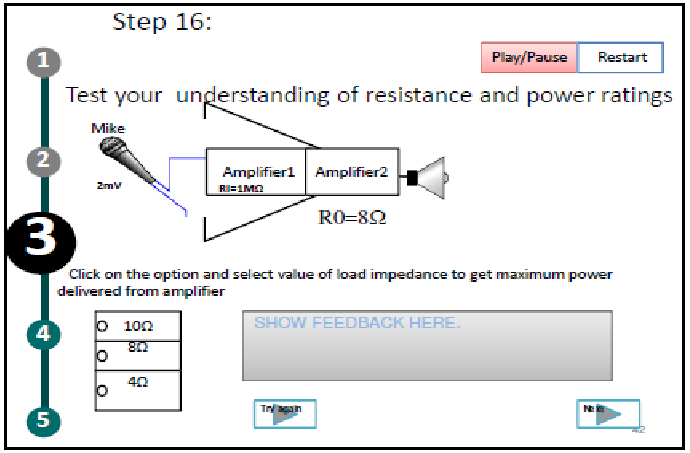

Step 11:
Play/Pause
Restart
1.56W
Mike
2mV
Amplifier1
RI=1MΩ
Amplifier2
4 Ω
R0=4Ω
Power in Watts
Load Resistor in Ω
37


Step 12:
Play/Pause
Restart
1.54W
Mike
2mV
Amplifier1
RI=1MΩ
Amplifier2
5 Ω
R0=4Ω
Power in Watts
Load Resistor in Ω
38


Step 13:
Play/Pause
Restart
1.5W
Mike
2mV
Amplifier1
RI=1MΩ
Amplifier2
6Ω
R0=4Ω
Power in Watts
Load Resistor in Ω
39


Step 14:
Play/Pause
Restart
1.38W
Mike
2mV
Amplifier1
RI=1MΩ
Amplifier2
8Ω
R0=4Ω
Power in Watts
Load Resistor in Ω
40



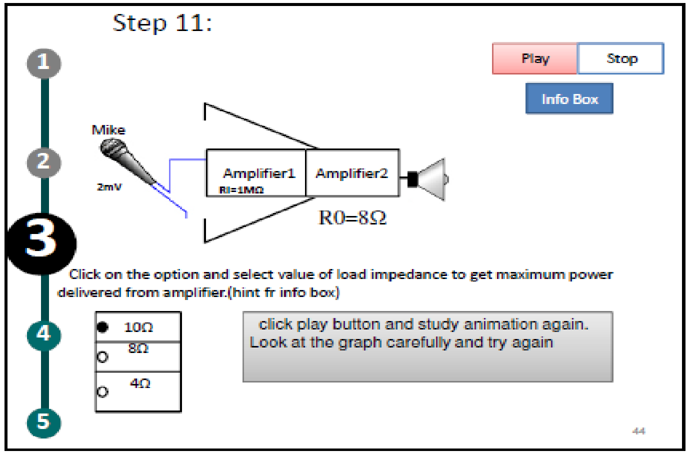


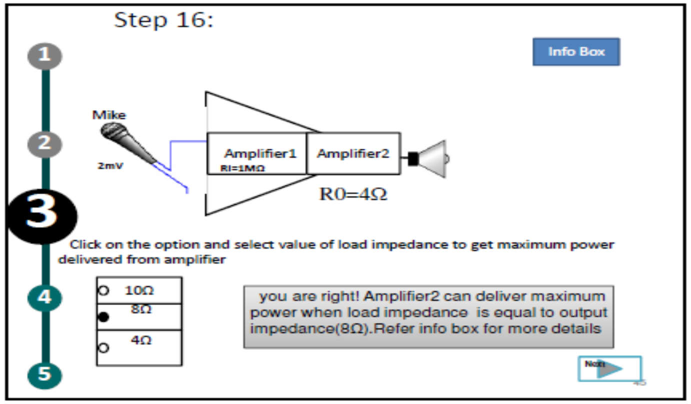
Description of the action/ interactivity

REFER the template (Master Slide) on Slide number 9 for all instructions below

1. Show the question and options with buttons as shown.
2. When user will select option 1 or 3 ,Display slide no.44 or 47.allow user to click "play button". When user clicks play button show slide no 32.
3. If user clicks option 2thenshow slide no.44 display info box button and allow user to click it . When user clicks info box show slide no. 46 . Then show NEXT button .

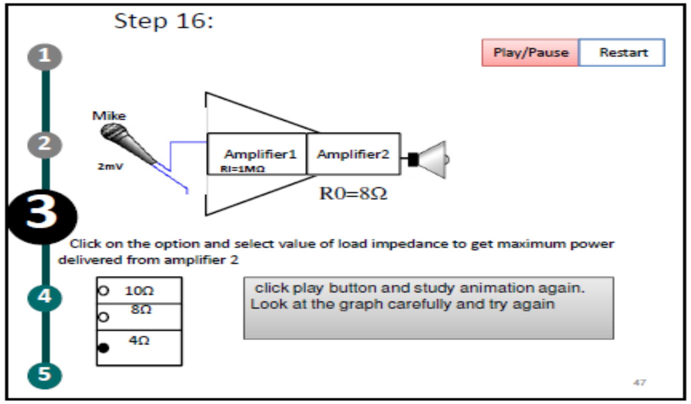
43





The **Maximum Power Transfer Theorem** states that the maximum amount of power will be delivered to the load impedance when the value of the load impedance is exactly equal to the output impedance of the power amplifier. This is known as impedance matching.

46



Design Tip

While designing power amplifier "impedance matching "need to be ensured.

48

Welcome

- This is a document to explains the chosen concept to the animator.
- This will take you through a **5 section** process to provide the necessary details to the animator before starting the animation.
- The legend on the left will indicate the current status of the document. The big **Black** colored number will denote the current section, the Grey color would denote the completed sections, and the Turquoise color would denote the remaining sections.
- The slides having yellow background (like this one) are the 'Instruction slides'

3

Power Amplifier Design-

This learning object is created to explain important concepts related to power amplifier design

Related LOs:

- Prior Viewing: Design of voice paging system(deciding specifications)
- Future Viewing: Deciding Class of amplifier

Course Name: Electronics Circuits
Level(UG/PG):UG
Author(s) : Madhuri Mavinkurve
Mentor(s):Prof.Sahana Murthy

4

Learning objectives

- Students should be able to identify efficiency and linearity are important specifications to decide power amplifier in design of voice paging system.
- Students should be able to select type of power amplifier for given voice paging application based on efficiency and linearity.

5

IMPORTANT NOTE TO THE ANIMATOR:

•All the instructions/labels or anything WRITTEN in blue are CONTENT NOT TO BE DISPLAYED!

•All the instructions WRITTEN in black are CONTENT TO BE DISPLAYED!

•This is not applicable for images as there can be overlapping of these colours there. This should be followed for all the instructions, labels,etc...

Kindly keep a note of this while displaying text in the animation.

6

Master layout or diagram

1

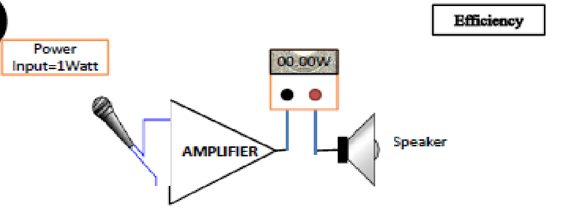
- Make a schematic diagram of the concept
- Explain to the animator about the beginning and ending of the process.
- Draw image big enough for explaining.
- In above image, identify and label different components of the process/phenomenon. (These are like characters in a film)Illustrate the basic flow of action by using arrows.
- Use BOLD lines in the diagram, (minimum 2pts.)In the slide after that, provide the definitions of ALL the labels used in the diagram
- You may have multiple master layouts.
  - In this case, number the master layout. (e.g. Master layout 1)
  - Each Master layout should be followed by the stepwise description of the animation stages related to it.

2 3 4 5

7

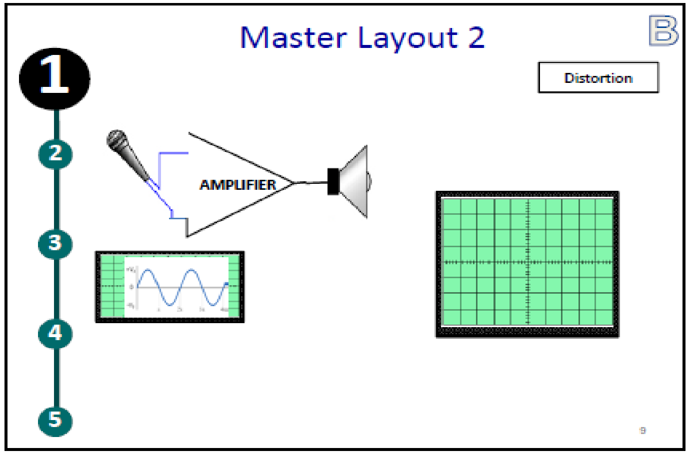
Master Layout 1

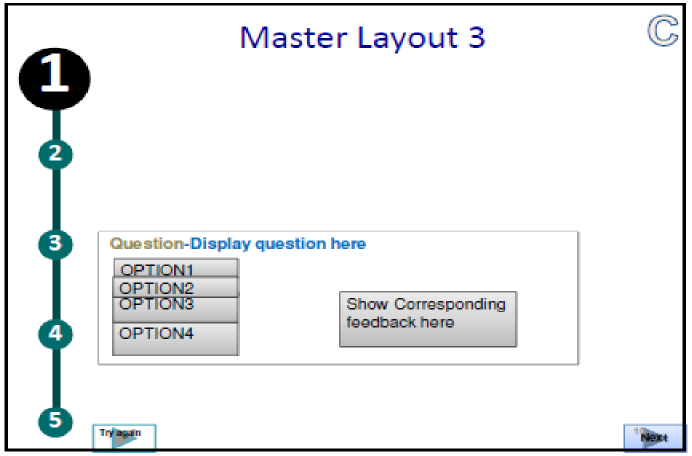
1

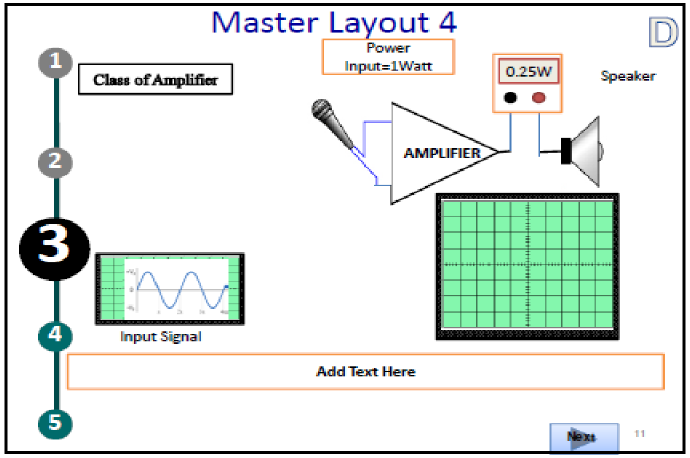


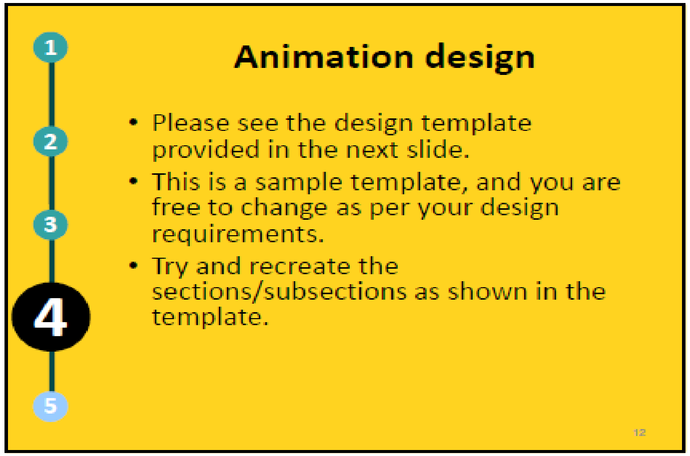
2 3 4 5

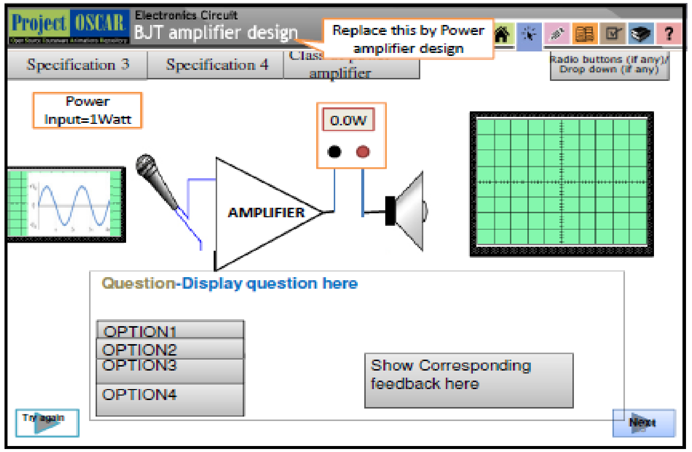
8


Master Layout 2
B
1
2
3
4
5
Distortion
AMPLIFIER


Master Layout 3
C
1
2
3
4
5
Question-Display question here
OPTION1
OPTION2
OPTION3
OPTION4
Show Corresponding feedback here
Next


Master Layout 4
D
1
2
3
4
5
Class of Amplifier
Power Input=1Watt
0.25W
Speaker
AMPLIFIER
Input Signal
Add Text Here
Next


1
2
3
4
5
Animation design
• Please see the design template provided in the next slide.
• This is a sample template, and you are free to change as per your design requirements.
• Try and recreate the sections/subsections as shown in the template.



Stepwise description of process

- The goal of the document is to provide instructions to an animator who is not a expert.
- You have to describe what steps the animator should take to make your concept come alive as a moving visualization.
- Use one slide per step. This will ensure clarity of the explanation.
- Add a image of the step in the box, and the details in the table below the box.
- You can use any images for reference, but mention about it's copyright status
- The animator will have to re-draw / re-create the drawings
- *Add more slides as per the requirement of the animation*

14

Step 1:

Specification 3	Specification 4	Class of power amplifier

Description of the action/ interactivity	
1.Show 3 clickable buttons as shown in this slide .show corresponding texts like specification3, specification4,classes of power amplifier. 2.Initial screen should display all these buttons.	

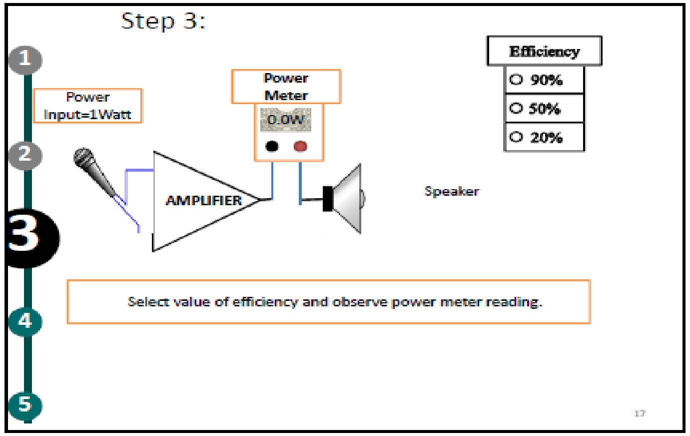
15

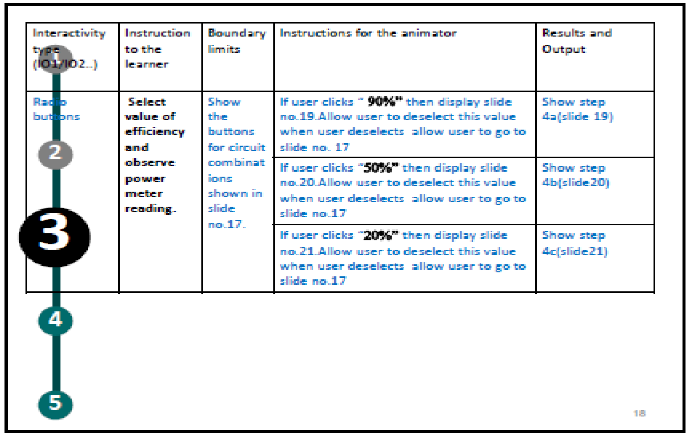
Step 2:

Specification 3	Specification 4	Class of power amplifier

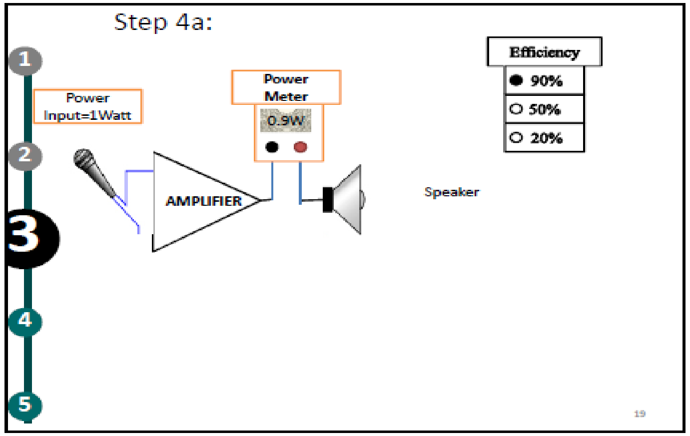
Description of the action/ interactivity	
1.Initial screen should display all the buttons mentioned in step1 2.If specification3 is clicked by user then dark the button as shown in this slide. and then show slide no17 and keep the button dark till slide no 28 is completed OR If specification4 is clicked by user then go to Slide 29 and keep button dark till slide no. OR If Classes of amplifier is clicked by user then go to Slide *****	

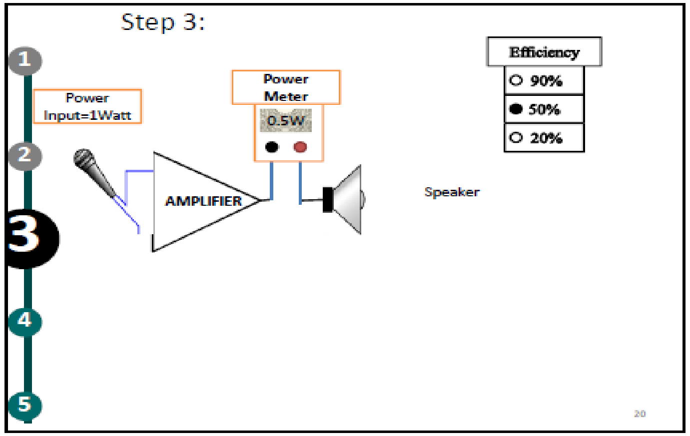
16

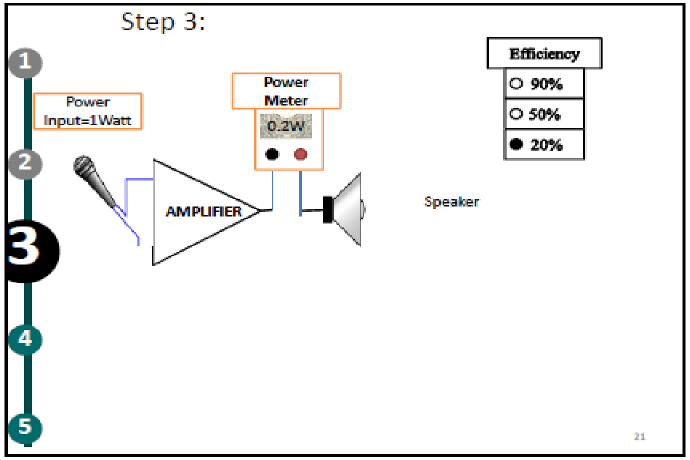


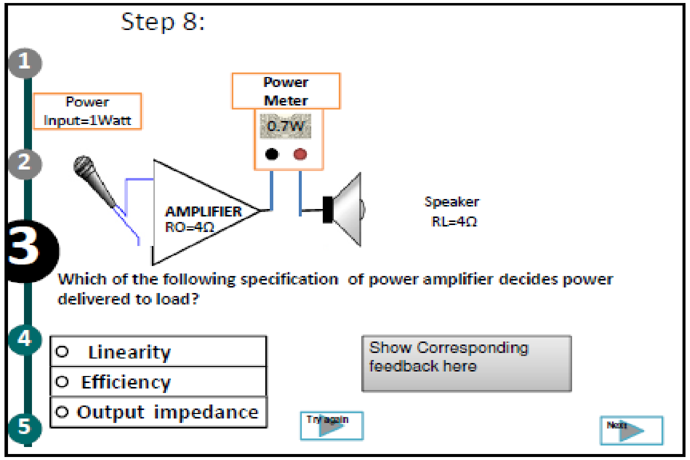


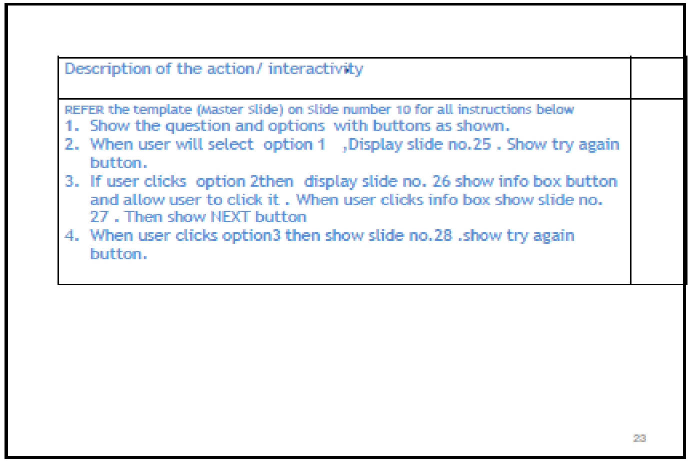
Interactivity type (IO1/IO2..)	Instruction to the learner	Boundary limits	Instructions for the animator	Results and Output
Radio buttons	**Select value of efficiency and observe power meter reading.**	Show the buttons for circuit combinations shown in slide no.17.	If user clicks " **90%"** then display slide no.19.Allow user to deselect this value when user deselects allow user to go to slide no. 17	Show step 4a(slide 19)
			If user clicks "**50%"** then display slide no.20.Allow user to deselect this value when user deselects allow user to go to slide no.17	Show step 4b(slide20)
			If user clicks "**20%"** then display slide no.21.Allow user to deselect this value when user deselects allow user to go to slide no.17	Show step 4c(slide21)

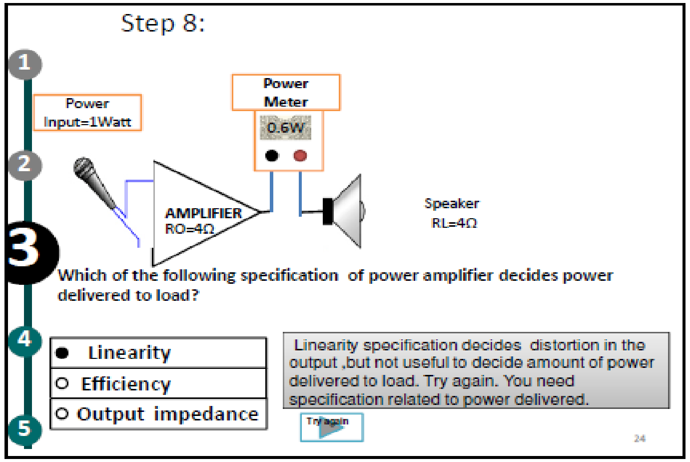


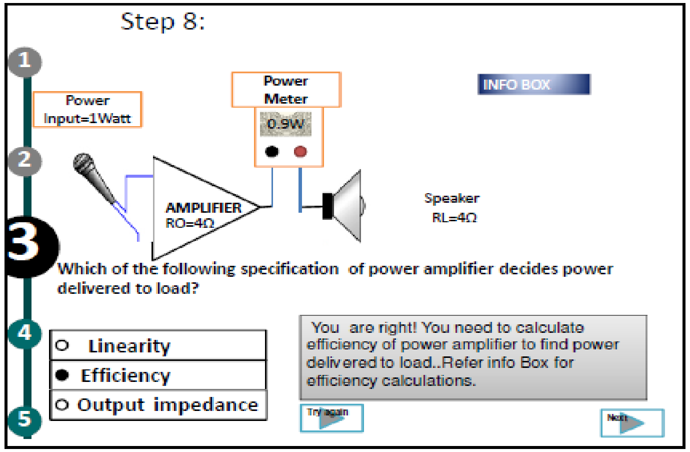


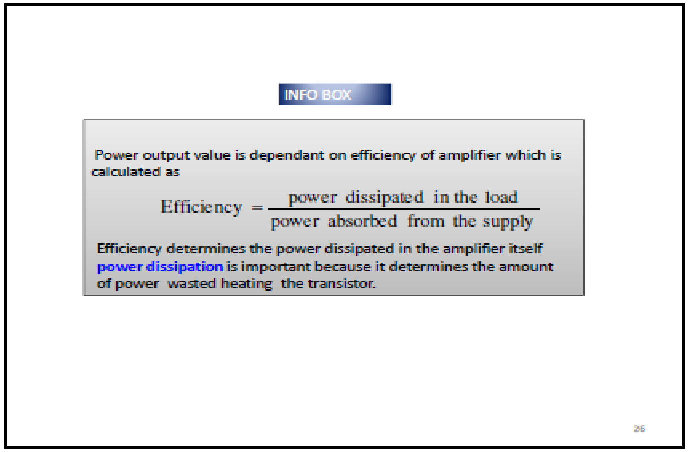

Step 3:
Power Input=1Watt
Power Meter
0.2W
AMPLIFIER
Speaker
Efficiency
90%
50%
20%
1
2
3
4
5
21

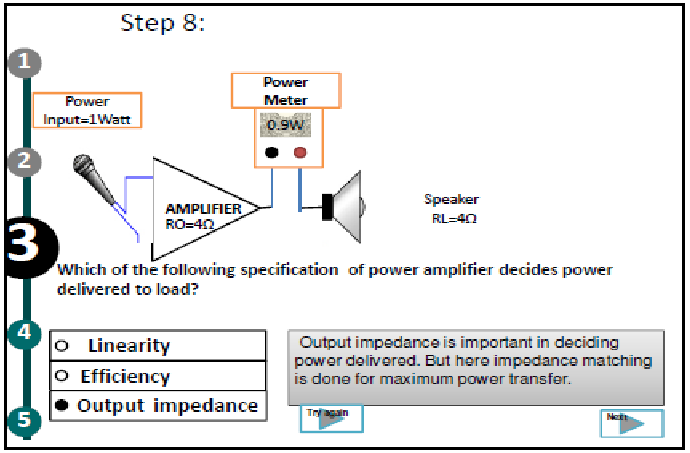

Step 8:
Power Input=1Watt
Power Meter
0.7W
AMPLIFIER
RO=4Ω
Speaker
RL=4Ω
Which of the following specification of power amplifier decides power delivered to load?
Linearity
Efficiency
Output impedance
Show Corresponding feedback here
Try again
Next
1
2
3
4
5

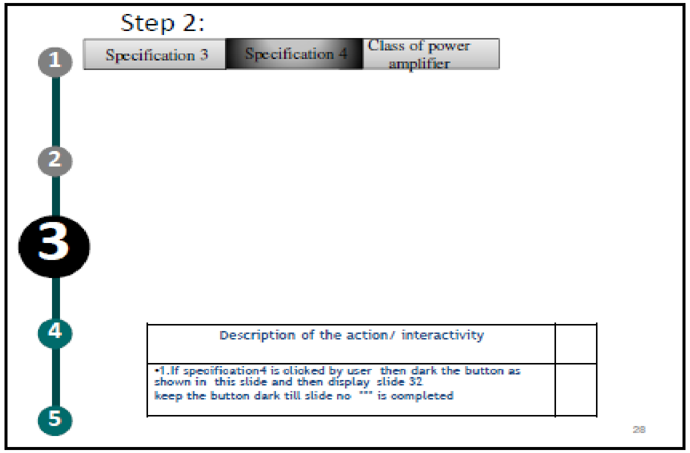

Description of the action/ interactivity
REFER the template (Master slide) on slide number 10 for all instructions below
1. Show the question and options with buttons as shown.
2. When user will select option 1 ,Display slide no.25 . Show try again button.
3. If user clicks option 2then display slide no. 26 show info box button and allow user to click it . When user clicks info box show slide no. 27 . Then show NEXT button
4. When user clicks option3 then show slide no.28 .show try again button.
23

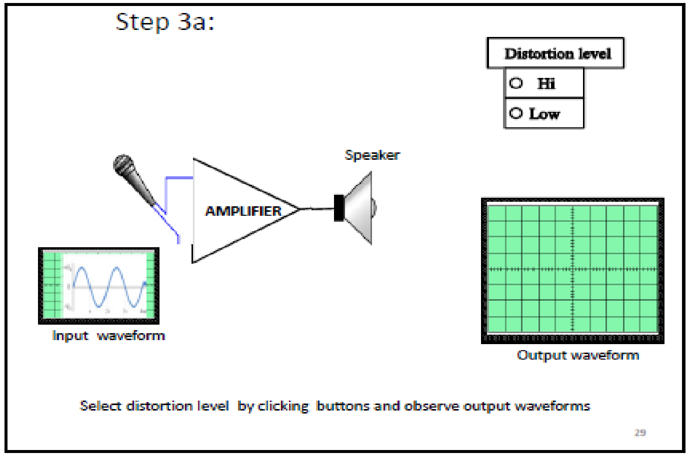

Step 8:
Power Input=1Watt
Power Meter
0.6W
AMPLIFIER
RO=4Ω
Speaker
RL=4Ω
Which of the following specification of power amplifier decides power delivered to load?
Linearity
Efficiency
Output impedance
Linearity specification decides distortion in the output ,but not useful to decide amount of power delivered to load. Try again. You need specification related to power delivered.
Try again
1
2
3
4
5
24


Step 8:
1
2
3
4
5
Power Input=1Watt
Power Meter
0.9W
AMPLIFIER
RO=4Ω
Speaker
RL=4Ω
INFO BOX
Which of the following specification of power amplifier decides power delivered to load?
Linearity
Efficiency
Output impedance
You are right! You need to calculate efficiency of power amplifier to find power delivered to load..Refer info Box for efficiency calculations.
Try again
Next


INFO BOX
Power output value is dependant on efficiency of amplifier which is calculated as
Efficiency = power dissipated in the load / power absorbed from the supply
Efficiency determines the power dissipated in the amplifier itself
power dissipation is important because it determines the amount of power wasted heating the transistor.
26

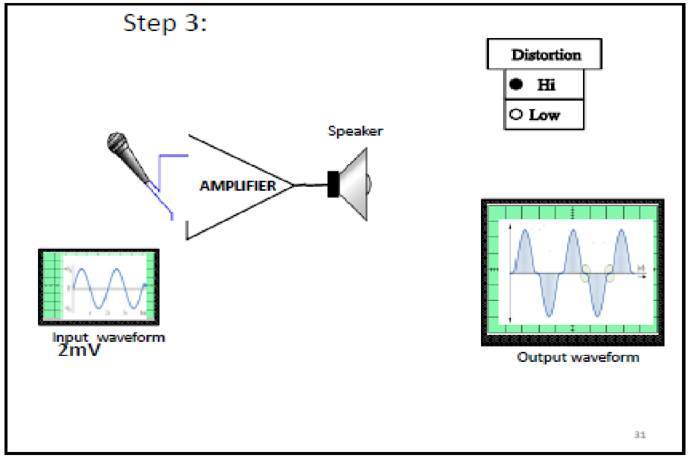

Step 8:
1
2
3
4
5
Power Input=1Watt
Power Meter
0.9W
AMPLIFIER
RO=4Ω
Speaker
RL=4Ω
Which of the following specification of power amplifier decides power delivered to load?
Linearity
Efficiency
Output impedance
Output impedance is important in deciding power delivered. But here impedance matching is done for maximum power transfer.
Try again
Next

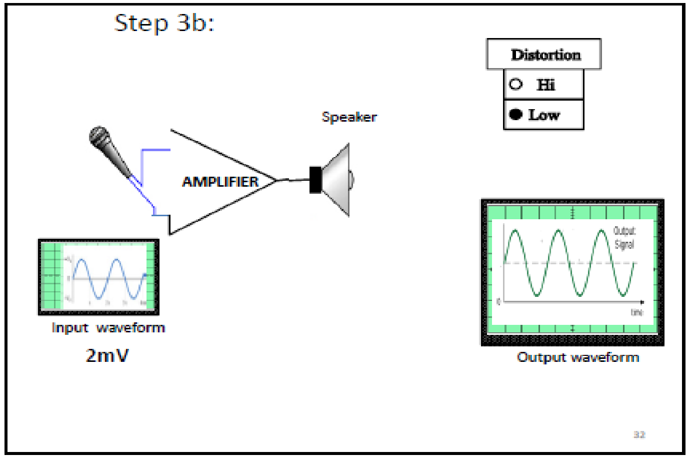

Step 2:
Specification 3
Specification 4
Class of power amplifier
1
2
3
4
5
Description of the action/ interactivity
•1.If specification4 is clicked by user then dark the button as shown in this slide and then display slide 32
keep the button dark till slide no "" is completed
28

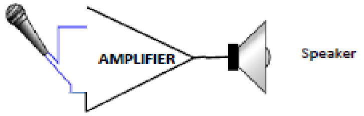


Interactivity type (IO1/IO2..)	Instruction to the learner	Boundary limits	Instructions for the animator	Results and Output
Radio buttons	**Select distortion level by clicking buttons and observe output waveforms**	Show the buttons for circuit combinations shown in slide no.29.	If user clicks " **Hi**" then display slide no.31.Allow user to deselect this value when user deselects allow user to go to slide no. 29	Show step 3a(slide 31)
			If user clicks "**LO**" then display slide no.32.Allow user to deselect this value when user deselects allow user to go to slide no.29	Show step 3b(slide32)

30







Which of the following specification of power amplifier decide distortion level in the output waveform?

- ○ Linearity of power amplifier
- ○ Output signal amplitude
- ○ efficiency of power amplifier

Show Corresponding feedback here

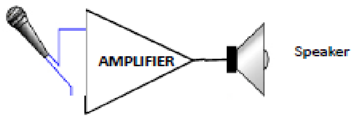
Try again

Next

Description of the action/ interactivity	
REFER the template (Master Slide) on slide number 10 for all instructions below 1. Show the question and options with buttons as shown. 2. When user will select option 1 ,Display slide no.35 . show info box button and allow user to click it . When user clicks info box show slide no. 38 . Then show NEXT button 3. If user clicks option 2 then display slide no. 36.Then show info box button and allow user to click it . When user clicks info box show slide no. 38 .Then Show try again button. 4. When user clicks option3 then show slide no.37 . Then show info box button and allow user to click it . When user clicks info box show slide no. 38 .Then Show try again button.	

34

INFO BOX



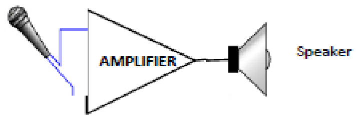
Which of the following specification of power amplifier decide distortion level in the output waveform?

- ● Linearity of power amplifier
- ○ Output signal amplitude
- ○ efficiency of power amplifier

Linearity specification decides distortion level the output waveform. Refer to info box for more details

Next

INFO BOX



Which of the following specification of power amplifier decide distortion level in the output waveform?

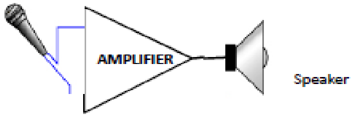
- ○ Linearity of power amplifier
- ● Output signal amplitude
- ○ efficiency of power amplifier

Amplitude of output signal cannot decide distortion level. Refer info box and try again.

Try again

36

INFO BOX



Which of the following specification of power amplifier decide distortion level in the output waveform?

- ○ Linearity of power amplifier
- ○ Output signal amplitude
- ● efficiency of power amplifier

Efficiency will decide power delivered to load ,but not a useful parameter to decide distortion level of output waveform. Refer info box and try again

Try again

37

Write info box as per guideline

INFO BOX

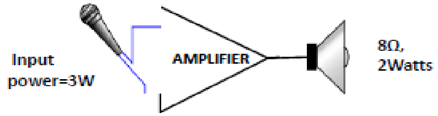
Distortion in output waveform mainly results due to non linearity of amplifier operation. Distortion can be controlled by selecting appropriate biasing circuit for amplifier.

38

Design Tip

- If power amplifier is operated in linear region then it produces faithful amplification i.e. input is reproduced properly. This is known as **high fidelity** and is useful property audio power amplifiers.

39



In above application amplifier should drive speaker load of 8Ω with power requirement of 2W with low fidelity so which is suitable specification to design power amplifier?

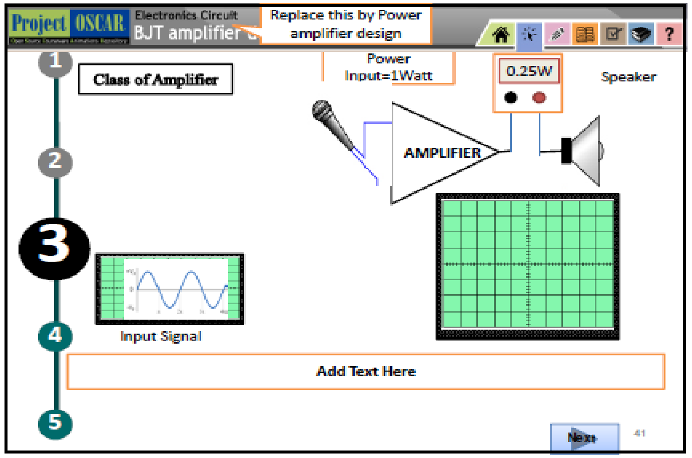
Linearity

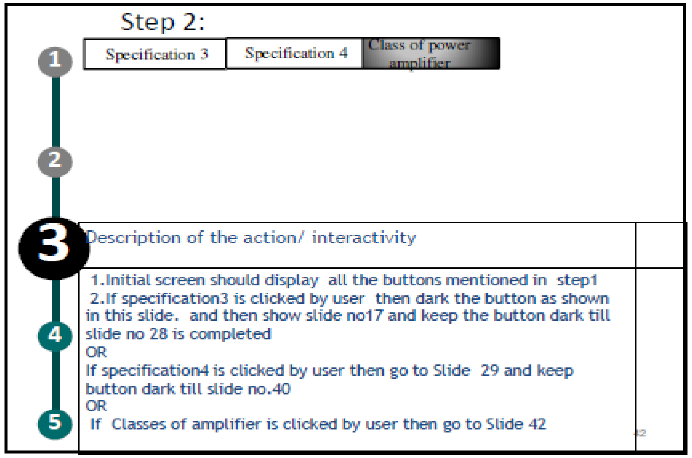
Linearity decides distortion and not power output . Refer and click specification2,3 button for details. Try again

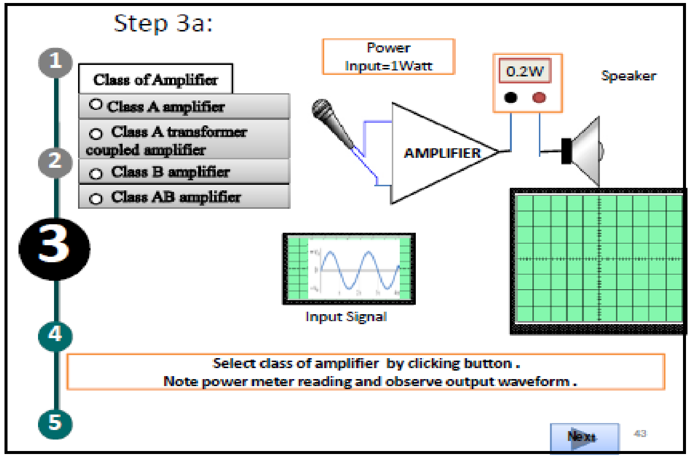
Efficiency

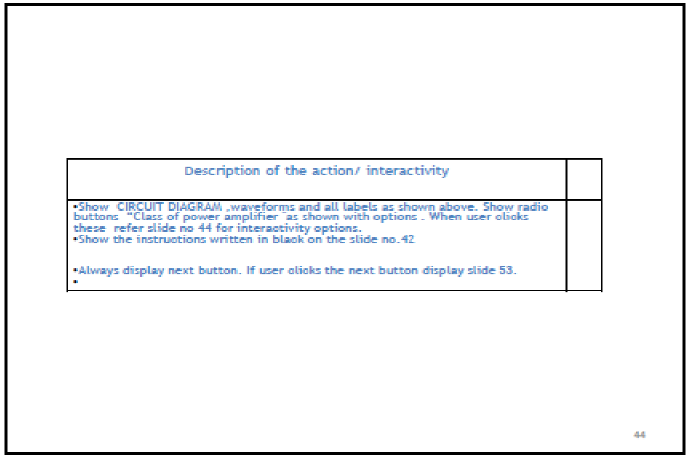
You are right! From available power input of 3W .Load demands 2W. You need to decide efficiency of power amplifier. Refer specification 3 button for more details

40


Project OSCAR
Electronics Circuit
BJT amplifier
Replace this by Power amplifier design
1
2
3
4
5
Class of Amplifier
Power Input=1Watt
0.25W
Speaker
AMPLIFIER
Input Signal
Add Text Here
Next
41

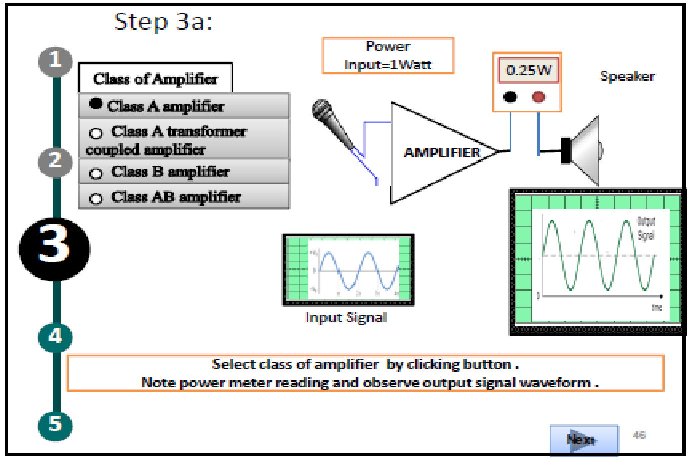

Step 2:
Specification 3
Specification 4
Class of power amplifier
1
2
3
4
5
Description of the action/ interactivity
1.Initial screen should display all the buttons mentioned in step1
2.If specification3 is clicked by user then dark the button as shown in this slide. and then show slide no17 and keep the button dark till slide no 28 is completed
OR
If specification4 is clicked by user then go to Slide 29 and keep button dark till slide no.40
OR
If Classes of amplifier is clicked by user then go to Slide 42
42

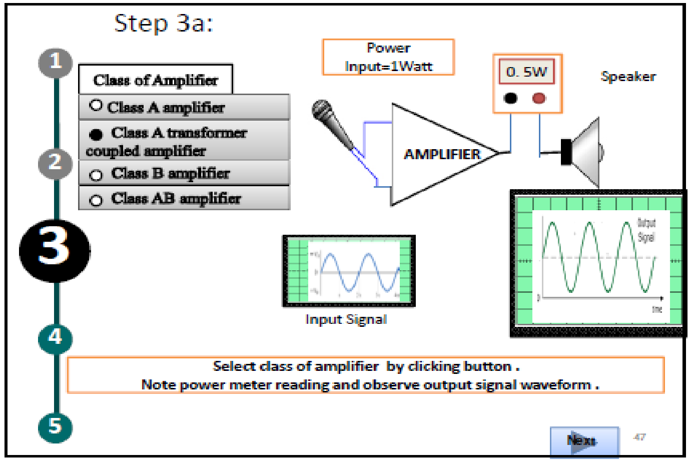

Step 3a:
1
2
3
4
5
Class of Amplifier
Class A amplifier
Class A transformer coupled amplifier
Class B amplifier
Class AB amplifier
Power Input=1Watt
0.2W
Speaker
AMPLIFIER
Input Signal
Select class of amplifier by clicking button .
Note power meter reading and observe output waveform .
Next
43

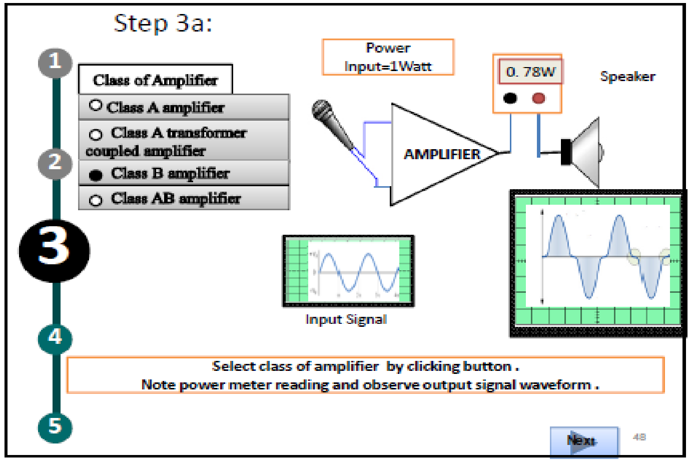

Description of the action/ interactivity
•Show CIRCUIT DIAGRAM ,waveforms and all labels as shown above. Show radio buttons "Class of power amplifier "as shown with options . When user clicks these refer slide no 44 for interactivity options.
•Show the instructions written in black on the slide no.42
•Always display next button. If user clicks the next button display slide 53.
•
44

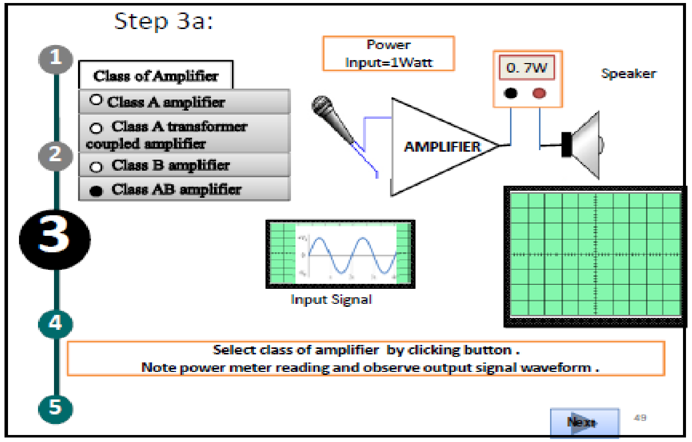
Interactivity type (IO1/IO2..)	Instruction to the learner	Boundary limits	Instructions for the animator	Results and Output
Radio buttons	Select class of power amplifier Note power meter reading and output waveform.	Show the buttons for circuit combinat ions shown in slide no.45	If user clicks "**Class A amplifier**" then display slide no.48.Allow user to deselect this value when user deselects allow user to go to slide no.45	Show step 16a(slide 48)
			If user clicks "**Class A transformer coupled amplifier**" then display slide no.49.Allow user to deselect this value when user deselects allow user to go to slide no.45	Show step 16b(slide49)
			If user clicks "**Class B amplifier**" then display slide no.50.Allow user to deselect this value when user deselects allow user to go to slide no.45	Show step 16c(slide50
			If user clicks "**Class AB amplifier**" then display slide no.51.Allow user to deselect this value when user deselects allow user to go to slide no.45	Show step 16d(slide51)

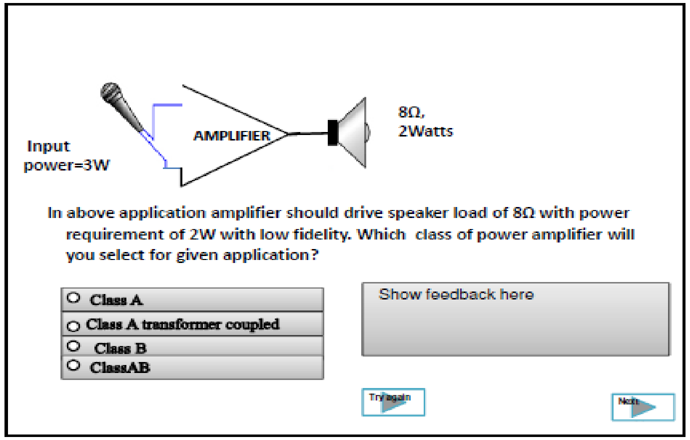
45





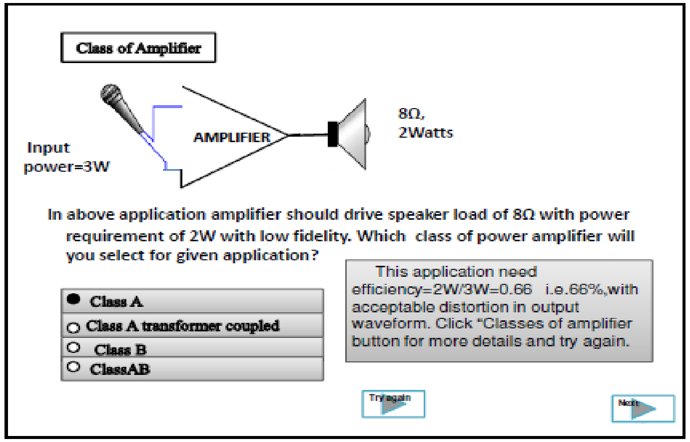




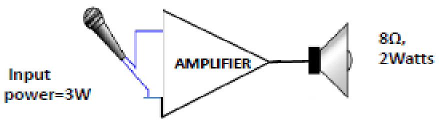


Description of the action/ interactivity	
REFER the template (Master Slide) on Slide number 10 for all instructions below 1. Show the question and options with buttons as shown. 2. When user will select option 1 ,Display slide no.51 . show "classes of amplifier button. Allow user to click this button and when user clicks this button go to slide no 43. 3. If user clicks option 2 then display slide no. 52. show "classes of amplifier button. Allow user to click this button and when user clicks this button go to slide no 43. 4. If user clicks option 2 then display slide no. 53. show "classes of amplifier button. Allow user to click this button and when user clicks this button go to slide no 43 5. If user clicks option 2 then display slide no. 54. show "classes of amplifier button. Allow user to click this button and when user clicks this button go to slide no 43	

51



Class of Amplifier



In above application amplifier should drive speaker load of 8Ω with power requirement of 2W with low fidelity. Which class of power amplifier will you select for given application?

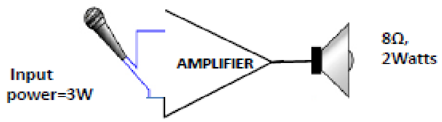
- ○ Class A
- ● Class A transformer coupled
- ○ Class B
- ○ ClassAB

This application need efficiency=2W/3W=0.66 i.e.66%,with acceptable distortion in output waveform. Click "Classes of amplifier button for more details .

Try again

Next

Class of Amplifier



In above application amplifier should drive speaker load of 8Ω with power requirement of 2W with low fidelity. Which class of power amplifier will you select for given application?

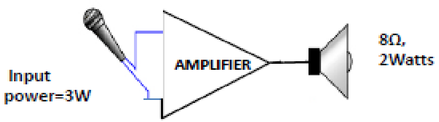
- ○ Class A
- ○ Class A transformer coupled
- ● Class B
- ○ ClassAB

This can be correct answer. This application need efficiency=2W/3W=0.66 i.e.66%,with acceptable distortion in output waveform. Refer "Classes of amplifier for more details

Try again

Next

Class of Amplifier



In above application amplifier should drive speaker load of 8Ω with power requirement of 2W with low fidelity. Which class of power amplifier will you select for given application?

- ○ Class A
- ○ Class A transformer coupled
- ○ Class B
- ● ClassAB

This can be correct answer. This application need efficiency=2W/3W=0.66 i.e.66%,with acceptable distortion in output waveform. Refer "Classes of amplifier for more details.

Try again

Next

Design Tip

If any application demands high efficiency the we need to compromise on linearity .

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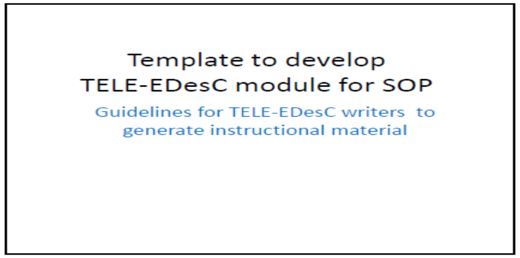
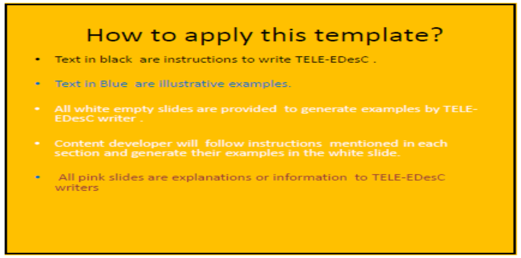
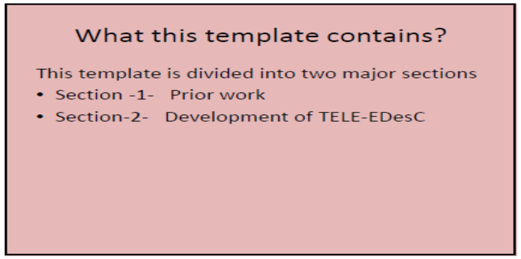
Appendix-III

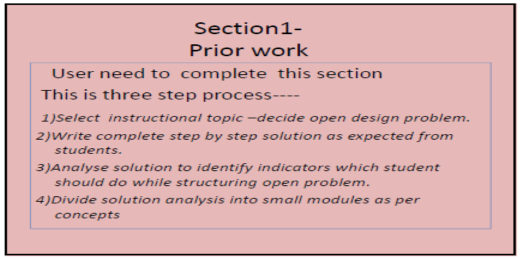
Template for writing TELE-EDesC

3.1. Template for writing TELE-EDesC









1 –step1-select instructional content Identification of problem

- Select instructional topic—
- E.g. Amplifier design –(gain bandwidth, impedance)

1 –step1-select instructional content Identification of problem

- Select open design problem which will cover instructional topic adequately.
- What is open design problem?
- Problem statements does not contain clear design goals or requirements instead designer need to identify goals.
- In this type of problems designers need to decide type of designs its pros and cons and justify the designed product based on goals.
- This type of problems can have multiple solutions
- .

Example

You need to record 1 mV signal for analysis. Recorder requires minimum 1V to record . Signal frequency varies between 10Hz to 100KHz. Source of signal and recorder should not be overloaded. Design a circuit.

1-step2- Problem Solution

- Write complete solution to the identified problem step by step (as expected from learners)
- Part of analysis is shown below as example
- *In amplifier design input voltage and expected output voltage is given so calculate*
- *gain=output voltage /input voltage.*
- *If frequency range is given then calculate bandwidth. Identify requirements of impedance*
- *All above specifications will be used to decide number of stages in the amplifier design as well as type of devices in the circuit.*

Write complete solution-

Section 1-step3

Why this step?

- This step will provide indicators that student should be able to do while structuring open problem.

What this step contains?

- There are four steps which are based on sub competencies identified for main competency (Structure open problem).
- Sub competencies are measurable units of main competencies

1-Step3.. Solution analysis

Step1:

A)Identify what are goals /specifications/ design requirement of problem from solution .

- *E.g. In the open problem gain , bandwidth, impedance are specifications /design goals/requirements.*

1-step3.. Solution analysis

- *Step2:*

B)Identify and list key decision steps from problem solution .

- *E.g. For given gain how many stages are required? Which device need to be used to attain given impedance etc.*

1-step3.. Solution analysis

Step3:

C)Identify sequence of decision steps

- *E.g. 1.Identification of gain as high gain.*
- *2.Selection of circuit to satisfy high gain.*
- *3.Think of given bandwidth*
- *4. Decide whether selected circuit can satisfy bandwidth specification.*
- *5.Consider impedance specification and decide active devices.*
- *6.Consider which circuit to design first .*

1-step3.. Solution analysis

Step 4:

D)Write structured statement—

Example :Design single/multistage amplifier with BJT/FET/combination with gain value/bandwidth etc.

Section 2— Development of TELE-EDesC

This section contains two parts

- *1-Prepare small modules. Divide entire solution analysis into small modules. Instructional content of these modules are decided as per guidelines given .*
- *2—Writing Learning objectives*
- *3-writing Learning dialogs*

2.2-Prepare Small modules

- Identify important concepts used to write structured design problem.
- Each module will contain only one concept .
- *E.g. Concept identified in amplifier design is relation between gain and bandwidth*

2.2-Prepare Small modules

- 1.Identify facts to be recalled.
- *Gain calculation and bandwidth calculations are facts to be recalled*

2.2-Prepare Small modules

- 2.Decide principles to be taught to help students to take decisions.
- Student should know --Product of gain and bandwidth is constant.

2.2-Prepare Small modules

- 3.Decide decision steps to be followed.
- Identification of gain as high or low is first step then identification of bandwidth high or low is second step etc

Content of module will be listed as follows

- Facts—
- Principles-
- Sequence of decision steps--

2-2..Learning Objectives

Write learning objectives .

1) *What is learning objective(LO)?*

(LO is specific, measurable performance outcome of student.)

2)How to write LO?

Each step from solution analysis is used to write learning objective.

1.Student should be able to identify and interpret relevant specifications/design goals/design requirements from given open problem.

Example:

- *Students should be able to identify gain is important specification in design of amplifier.*
- *Student should be able to calculate gain of given system*

Use solution analysis step1 - write learning objective

- Students should able to identify frequency band for given application.
- Students should able to calculate dimension of patch.
- Students should able to calculate feed location.

2-1..Learning Objectives

. 2.Students should be able to decide important structures like circuits/components/blocks/systems based on specification.

Example:

Students should able to decide number of stages in the amplifier circuit based on gain

Use solution analysis step2 -- write learning objective

- .

2-2..Learning Objectives

. 3.Student should able to sequence decision steps to structure open problem.

Example-

Student should calculate gain first and then decide circuit to satisfy gain requirements.

Use solution analysis step3 -- write learning objective

2-2..Learning Objectives

4. Student should able to write structured statements contain all specifications and structures.

Example :

Students should able to write statement like design of two stage /single stage BJT/FET amplifier for given gain and bandwidth

Use solution analysis step4 --- write learning objective

2. 3.Write Learning Dialogs

- For each learning objective write learning dialog
- Steps to write learning dialogs are given .

2.3.Write Learning Dialogs

- Learning objective 1

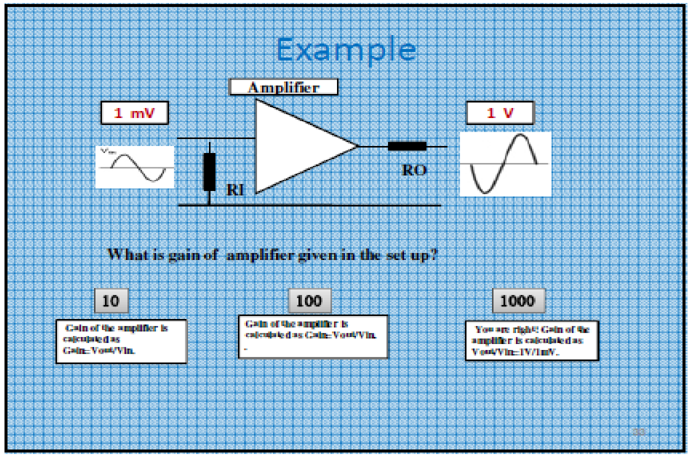
1.Student should able to identify relevant specifications/design goals/design requirements from given open problem.

A)Write concept clarification Question (CCQ) as per given guidelines

2-3-A.-Write CCQ

CCQ will contain

- *Question to test student's interpretation of design goals/specification/design requirements.*
- *Answers--Multiple plausible answers with one correct choice.*
- *Feedback –*
- *a) Explanation related to reasoning for why the answer is wrong*
- *b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .*
- *c) Feedback for correct answer also will explain why selected answer is correct(reasoning for correct answer)*



- Write CCQ for your Learning objective 1

2..2.Write Learning Dialogs

- Learning objective 1
- *1.Student should able to identify relevant specifications/design goals/design requirements from given open problem.*

B) Write Decision Making Task Question(DMTQ)

2..2-B.Write DMTQ

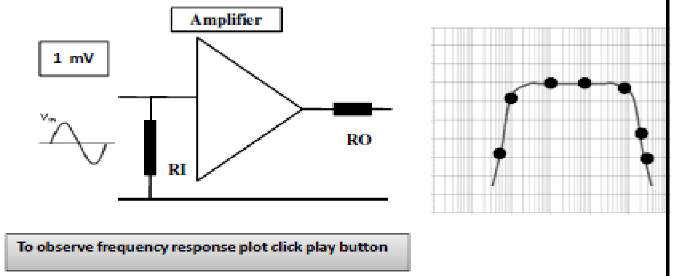
DMTQ will contain

- *Question to identify which is relevant specification from given set of specifications.*
- *Answers--Multiple plausible answers with one correct choice.*
- *Feedback –*
- *a) Explanation related to reasoning for why the answer is wrong*
- *b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .*
- *c) Feedback for correct answer also will explain why selected answer is correct(reasoning for correct answer)*

Example

- For amplifier design bandwidth specification is selected, which need graph to represent bandwidth.
- To shown concept of bandwidth we need semi-log paper
- We need gain variation with respect to frequency to show bandwidth.
- We form a table of frequency Vs gain and then plot point on semi-log paper.
- Show animation for each point separately on slides.
- Write actions expected for play, pause and stop button.

Animation will look as shown



Add animation as per guideline

2..3.Write instructional activities

- Learning objective 2
- *2.Students should be able to decide important structures like circuits/components/blocks/systems based on specification.*
- A)Write DMTQ and INFO Box.

2.2-A-Write DMTQ&INFO Box

- How to write Question?
- Question to decide important circuit/ block /system/components for given specifications.
- Include multiple representations .
- Answers-Multiple plausible mainly targeting misconceptions of students
- Feedback—

a) Explanation related to reasoning for why the answer is wrong

b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .

c) Feedback for correct answer also will explain why selected answer is correct(reasoning for correct answer) and leading students to next decision step

Example

- **Which of the following circuit combination can provide gain of 1000?**

Single stage BJT amplifier	Two stage BJT amplifier	Single stage FET amplifier	Two stage FET amplifier
Gain of 1000 is considered as high gain and single stage BJT amplifier is not sufficient to provide this gain. Refer Info Box	You are right! Gain of 1000 is high gain and two stage BJTamplifier can provide this gain. Refer info box for more details	Gain of 1000 is considered as high gain .While gain provided by FET amplifier is very low and thus single stage FET amplifier can not provide this gain. Refer Info box	Gain of 1000 is considered as high gain. But FET amplifier is low gain amplifier and two stage FET is not sufficient to provide this gain. Refer Info box

Write DMTQ as per guideline

2.3.-A-Write DMTQ&INFO Box

- What INFO Box will contain?
- Information which will help students to take decisions.
- Example

INFO BOX

Maximum gain of single stage BJT amplifier is approximately =100
Maximum gain of single stage FET amplifier is approximately =10
Gain of two stage amplifier is=gain of first stage*gain of second stage

Write info box as per guideline

2..3.Write instructional activities

- Learning objective 2
- *2.Students should be able to decide important structures like circuits/components/blocks/systems based on specification.*
- B)Include Variable manipulation

2.3-B-Write VM

- For writing VM activity TELE-EDesC writer need to follow following steps
- 1-Identification of part of solution analysis.
- 2-Writing VM activity.

2.3-B-step1-Write VM

- Identification of solution part—
- VM can be written for all of the following---
- Part of solution analysis in which different ideas need to be explored.
- Part of the solution in which students need to connect different specifications /design requirements/design goals to each other and then take decisions in design process. Thus VM will be designed based on concepts required to take key decisions in design process.

How to write VM?

- How to add variable manipulations?
- *Include variable manipulations such that students should be able to change input variables or parameters or conditions within system and can immediately observe corresponding changes in the output.*
- *Show Different representations simultaneously*
- *Add buttons to move forward,backward,increment ,decrement.*
- *Show Separate frame for each variation.*
- *TELE-EDesC writer need to select range depending on design requirements*
- *Feedback box to explain the effect of variations or follow up question answer feedback to test student's understanding from animation/variable manipulation etc.*

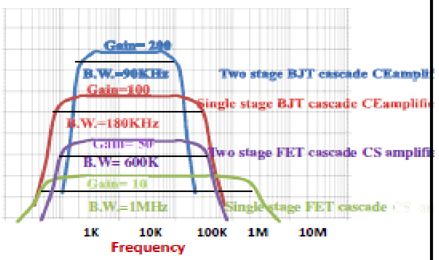
- Example--Select part of solution for VM-----
  Frequency response of different circuits is selected which need different circuits for different frequency responses and also convey concept of gain bandwidth product

---

2.3.-B-Write VM

Select given combination of circuits and observe frequency plots

- **Single stage BJT CE amplifier**
- **Two stage BJT cascade CEamplifier**
- **Single stage FET CS amplifier**
- **Two stage FET CS cascade amplifier**



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Write Variable Manipulation(VM)

2.3.Write instructional activities

- For each learning objective develop instructional activity as per the steps given below ------
- Learning objective—solution step3—

Decide overall sequence of decision steps.

Example--

Write sequence of decision steps

2.3.Write instructional activities

- For each learning objective develop instructional activity as per the steps given below ------
- Learning objective—solution step4—
- Include Conceptual design support . (CDS).
- These are important design concepts.

How to write them?

- Identify important keywords required to support decisions and order.
- *E.g. gain, bandwidth are important keywords.*

- Write important keywords which support decisions .

How to write them?

- Decide number of statements based on number of key decisions.
- *For key decisions two important design concepts are required*

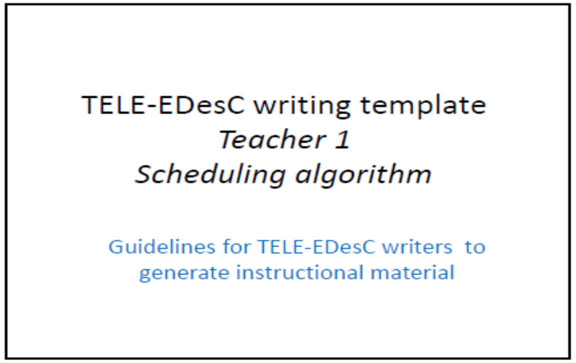
-

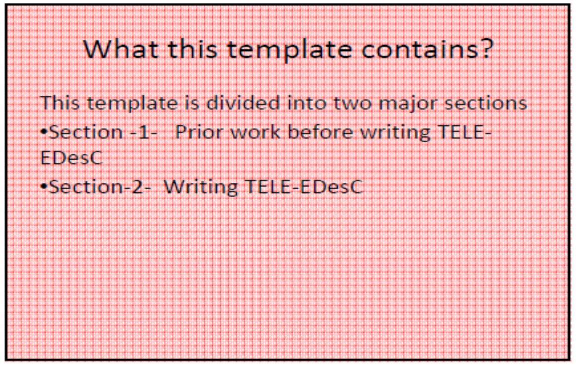
How to write them?

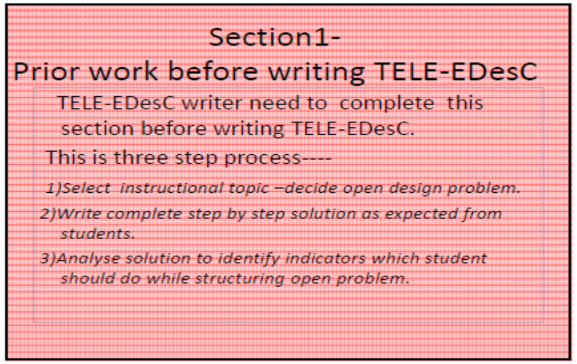
- Write the conceptual statements highlighting design keywords at each key decision step.
- *E.g. Gain –bandwidth product of given system is constant*.

- Write conceptual statement for your solution

3.2. Template to develop TELE-EDesC applied by teacher 1-Scheduling algorithm







1 –step1-select instructional content Identification of problem

- Select instructional topic—

•E.g. Amplifier design –(gain bandwidth, impedance)

Write your selected topic here

•Process Scheduling – Operating System

1 –step1-select instructional content Identification of problem

•Select open design problem which will cover instructional topic adequately.

•What is open design problem?

•Problem statements does not contain clear design goals or requirements instead designer need to identify goals.

•In this type of problems designers need to decide type of designs its pros and cons and justify the designed product based on goals.

•This type of problems can have multiple

Example

Write open design problem selected

•Write a program to choose the best scheduling policy given the list of processes.

1-step2- Problem Solution

• Write complete solution to the identified problem step by step (as expected from learners)

•Part of analysis is shown below as example

• In amplifier design input voltage and expected output voltage is given so calculate

• gain=output voltage /input voltage.

•If frequency range is given then calculate bandwidth. Identify requirements of impedance

•All above specifications will be used to decide number of

Write complete solution-

•Given the processes CPU burst times, arrival times , Priority and time quantum calculate the average waiting time and average turnaround time for FCFS, SJF, Priority and Round robin for each process

•Calculate average waiting time and turn around time for each process scheduling algorithm

•Compare the average waiting time and turn around time , the process scheduling algorithm with the least time will be the most appropriate scheduling algorithm

Section 1-step3

Why this step?

•This step will provide indicators that student should be able to do while structuring open problem.

What this step contains?

•There are four steps which are based on sub competencies identified for main competency (Structure open problem).

•Sub competencies are measurable units of main competencies

1-Step3.. Solution analysis

Step1:

A)Identify what are goals /specifications/ design requirement of problem from solution .

- *E.g. In the open problem gain , bandwidth, impedance are specifications /design goals/requirements.*

Write identified design goals/requirements /specifications

- The burst time, arrival time, priority and time quantum will be the design requirements/specification

1-step3.. Solution analysis

- *Step2:*

B)Identify and list key decision steps from problem solution .

- *E.g. For given gain how many stages are required? Which device need to be used to attain given impedance etc.*

Write important and key decision steps

- Calculation of waiting time and turn around time for each process

1-step3.. Solution analysis

Step3:

C)Identify sequence of decision steps

- *E.g. 1.Identification of gain as high gain.*
- *2.Selection of circuit to satisfy high gain.*
- *3.Think of given bandwidth*
- *4. Decide whether selected circuit can satisfy bandwidth specification.*
- *5.Consider impedance specification and decide active devices.*
- *6.Consider which circuit to design first .*

Identify sequence in which decisions need to be taken

- Input all the 3 important parameters for each process: CPU burst time, Arrival time, Priority
- For process scheduling additionally one more parameters have to be taken as input – Time quantum
- All the time parameters are in millisecond
- After the input is taken process scheduling is done using all the four algorithms FCFS, SJF, Priority and Round Robin
- During the process scheduling in each

1-step3.. Solution analysis

Step 4:

D)Write structured statement—

Example :Design single/multistage amplifier with BJT/FET/combination with gain value/bandwidth etc.

Write expected structured statement

- Write a program to choose the best scheduling policy given the list of processes

Section 2— Writing TELE-EDesC

This section contains two parts

1-Prepare small modules. Divide solution analysis into two modules.

- *a) First module will contain introduction of visible specifications and related concepts in the form of given data.*
- *b)Second module will contain hidden specifications which student need to decide for given application and its related concepts.*
- *c)Instructional content of these modules are decided as per guidelines given .*

Content of module will be listed as follows

- Facts—
  - Input to be collected for every process: CPU burst time, arrival time, priority
  - Time Quantum to be specified for Round Robin Process Scheduling
- Principles-
  - **Waiting time - amount of time a process has been waiting in the ready queue**
  - **Turnaround time – amount of time to execute a particular process**
- Sequence of decision steps–
  - First input the parameters
  - In every process scheduling algorithm , for every process calculate the waiting time and turn around time(tt)
  - For every process scheduling algorithm calculate average waiting time and tt
  - Process scheduling with the least average waiting time and tt will be the answer to the problem

2-2..Learning Objectives

Write learning objectives .

1) *What is learning objective(LO)?*

(LO is specific, measurable performance outcome of student.)

2)How to write LO?

Each step from solution analysis is used to write learning objective.

1.Student should be able to identify and interpret relevant specifications/design goals/design requirements from given open problem.

Example:

- *Students should be able to identify gain is important specification in design of amplifier.*
- *Student should be able to calculate gain of given system*

Use solution analysis step1 - write learning objective

- Student should be able to identify the input necessary for process scheduling.
  - For every process student would have to identify the
    - CPU burst time
    - Arrival time
    - Priority
  - Also the time quantum needs to be taken as input for Round Robin algorithm

2-1..Learning Objectives

. *2.Students should be able to decide important structures like circuits/components/blocks/systems based on specification.*

Example:

Students should able to decide number of stages in the amplifier circuit based on gain

Use solution analysis step2 -- write learning objective

- Student should be able to demonstrate the understanding of waiting time and tt by calculating the waiting time and tt for every process

2-2..Learning Objectives

. *3.Student should able to sequence decision steps to structure open problem.*

Example-

Student should calculate gain first and then decide circuit to satisfy gain requirements.

Use solution analysis step3 -- write learning objective

- Student should be able to calculate the waiting time and tt for every process and then find the average waiting time and tt for the specific process scheduling algorithm

2-2..Learning Objectives

4. Student should able to write structured statements contain all specifications and structures.

Example :

Students should able to write statement like design of two stage /single stage BJT/FET amplifier for given gain and bandwidth

Use solution analysis step4 --- write learning objective

- Student should be able to write statement on which of the process scheduling algorithm is better than any other based on the values of average waiting time and tt

2. 3.Write instructional activities

- For each learning objective write instructional activities.
- Steps to write instructional activities are given .

2.3.Write instructional activities

•Learning objective 1

1.Student should able to identify relevant specifications/design goals/design requirements from given open problem.

A)Write concept clarification Question (CCQ) as per given guidelines

2-3-A.-Write CCQ

CCQ will contain

•*Question to test student's interpretation of design goals/specification/design requirements.*

•*Answers--Multiple plausible answers with one correct choice.*

•*Feedback –*

•*a) Explanation related to reasoning for why the answer is wrong*

•*b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .*

2..2.Write instructional activities

•Learning objective 1

•*1.Student should able to identify relevant specifications/design goals/design requirements from given open problem.*

B) Write Decision Making Task Question(DMTQ)

2..2-B.Write DMTQ

DMTQ will contain

•*Question to identify which is relevant specification from given set of specifications.*

•*Answers--Multiple plausible answers with one correct choice.*

•*Feedback –*

•*a) Explanation related to reasoning for why the answer is wrong*

•*b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .*

Write DMTQ as per guidelines for learning objective1

- For Round Robin scheduling which additional input would be required?

a.Burst Time (Burst is necessary but not sufficient for Round Robin Scheduling)

b.Size of queue (This data is unnecessary for process scheduling)

c.Time Quantum (You are correct. Time Quantum is required additional to CPU Burst time and Arrival time)

2.2-C.Add Animation

- Select specification which may need either graph/waveform/circuit /blocks/process (representations) for explanation.
- Identify appropriate graph/circuits/waveform/block /process to represent specification.
- Identify parameters to be represented in graph/circuit/block /process.
- Describe relation between selected parameters either using tables or separate slides.

2..2.c.Write instructional activities

- For each learning objective develop instructional activity as per the steps given below ------
- Learning objective—solution step1—

c) Add Animation with visual feedback –

This will contain dynamically linked multiple representations.

Example

- For amplifier design bandwidth specification is selected, which need graph to represent bandwidth.
- To shown concept of bandwidth we need semi-log paper
- We need gain variation with respect to frequency to show bandwidth.
- We form a table of frequency Vs gain and then plot point on semi-log paper.
- Show animation for each point separately on slides.

2..3.Write instructional activities

- Learning objective 2
- *2.Students should be able to decide important structures like circuits/components/blocks/systems based on specification.*
- A)Write DMTQ and INFO Box.

2.2-A-Write DMTQ&INFO Box

- How to write Question?
- Question to decide important circuit/ block /system/components for given specifications.
- Include multiple representations .
- Answers-Multiple plausible mainly targeting misconceptions of students
- Feedback—

a) Explanation related to reasoning for why the answer is wrong

b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .

c) Feedback for correct answer also will explain why selected answer is correct(reasoning for correct answer) and leading students to next decision step

2..3.Write instructional activities

- Learning objective 2
- *2.Students should be able to decide important structures like circuits/components/blocks/systems based on specification.*
- B)Include Variable manipulation

2.3-B-Write VM

- For writing VM activity TELE-EDesC writer need to follow following steps
- 1-Identification of part of solution analysis.
- 2-Writing VM activity.

2.3-B-step1-Write VM

- Identification of solution part—
- VM can be written for all of the following---
- Part of solution analysis in which different ideas need to be explored.
- Part of the solution in which students need to connect different specifications /design requirements/design goals to each other and then take decisions in design process. Thus VM will be designed based on concepts required to take key decisions in design process.

How to write VM?

- How to add variable manipulations?
- *Include variable manipulations such that students should be able to change input variables or parameters or conditions within system and can immediately observe corresponding changes in the output.*
- *Show Different representations simultaneously*
- *Add buttons to move forward,backward,increment ,decrement.*
- *Show Separate frame for each variation.*

- Example--Select part of solution for VM-----Frequency response of different circuits is selected

  which need different circuits for different frequency responses and also convey concept of gain bandwidth product

Write Variable Manipulation(VM)

- Give the input box for the students as the Time Quantum (TQ in ms)
- As and when there is a change in the time quantum the gant chart changes in RR

2.3.Write instructional activities

- For each learning objective develop instructional activity as per the steps given below ------
- Learning objective—solution step3—

Decide overall sequence of decision steps.

Example--

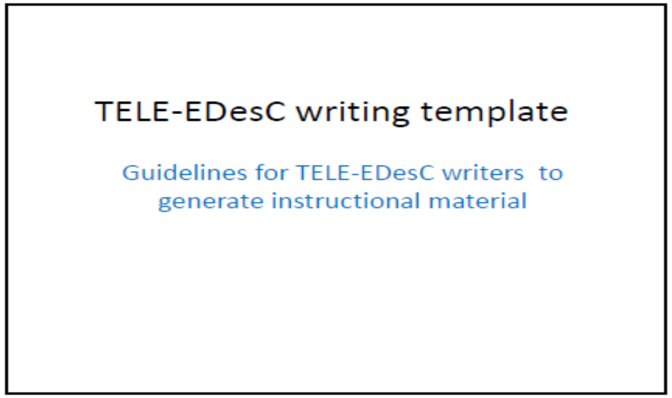
Write sequence of decision steps

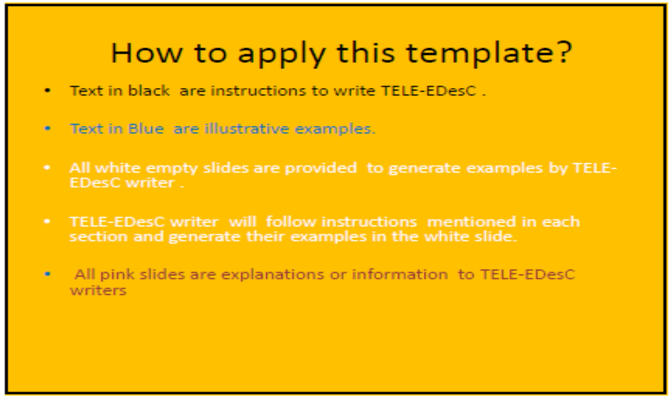
- Input all the 3 important parameters for each process: CPU burst time, Arrival time, Priority
- For process scheduling additionally one more parameters have to be taken as input – Time quantum
- All the time parameters are in millisecond
- After the input is taken process scheduling is done using all the four algorithms FCFS, SJF, Priority and Round Robin
- During the process scheduling in each

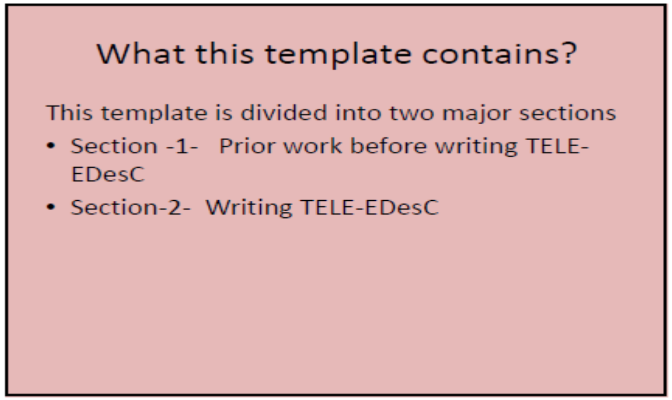
2.3.Write instructional activities

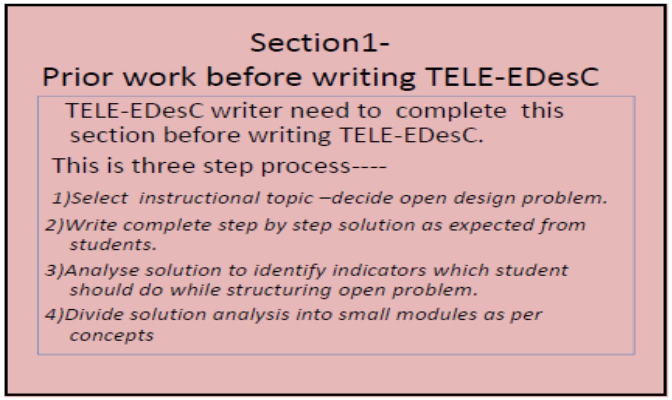
- For each learning objective develop instructional activity as per the steps given below ------
- Learning objective—solution step4—
- Include Conceptual design support . (CDS).
- These are important design concepts.

3.3. Template to develop TELE-EDesC applied by teacher 2-Antenna design









1 –step1-select instructional content Identification of problem

- Select instructional topic—
- E.g. Amplifier design –(gain bandwidth, impedance)

Write your selected topic here

- Microstrip Antenna design.

1 –step1-select instructional content Identification of problem

- Select open design problem which will cover instructional topic adequately.
- What is open design problem?
- Problem statements does not contain clear design goals or requirements instead designer need to identify goals.
- In this type of problems designers need to decide type of designs its pros and cons and justify the designed product based on goals.
- This type of problems can have multiple solutions

Example

Write open design problem selected

- Design a microstrip antenna for WLAN applications.

1-step2- Problem Solution

- Write complete solution to the identified problem step by step (as expected from learners)
- Part of analysis is shown below as example
- *In amplifier design input voltage and expected output voltage is given so calculate*
- *gain=output voltage /input voltage.*
- *If frequency range is given then calculate bandwidth. Identify requirements of impedance*
- *All above specifications will be used to decide number of stages in the amplifier design as well as type of devices in the circuit.*

Write complete solution-

- Decide the dielectric to be used (εr).
- Decide proper feeding technique
- Find dimensions of patch
- Find feed location.

Section 1-step3

Why this step?

- This step will provide indicators that student should be able to do while structuring open problem.

What this step contains?

- There are four steps which are based on sub competencies identified for main competency (Structure open problem).
- Sub competencies are measurable units of main competencies

1-Step3.. Solution analysis

Step1:

A)Identify what are goals /specifications/ design requirement of problem from solution .

- *E.g. In the open problem gain , bandwidth, impedance are specifications /design goals/requirements.*

Write identified design goals/requirements /specifications

- Specifications of Dielectric.
- Finding dimensions
- Feeding method

1-step3.. Solution analysis

- *Step2:*

B)Identify and list key decision steps from problem solution .

- *E.g. For given gain how many stages are required? Which device need to be used to attain given impedance etc.*

Write important and key decision steps

- Selection of Feeding method

1-step3.. Solution analysis

Step3:

C)Identify sequence of decision steps

- *E.g. 1.Identification of gain as high gain.*
- *2.Selection of circuit to satisfy high gain.*
- *3.Think of given bandwidth*
- *4. Decide whether selected circuit can satisfy bandwidth specification.*
- *5.Consider impedance specification and decide active devices.*
- *6.Consider which circuit to design first .*

Identify sequence in which decisions need to be taken

1-step3.. Solution analysis

Step 4:

D)Write structured statement—

Example :Design single/multistage amplifier with BJT/FET/combination with gain value/bandwidth etc.

Write expected structured statement

- Design inset feed Rectangular micro strip antenna for 2.4GHz WLAN application.

Section 2— Writing TELE-EDesC

This section contains two parts

- *1-Prepare small modules. Divide entire solution analysis into small modules. Instructional content of these modules are decided as per guidelines given .*
- *2—Writing Learning objectives*
- *3-writing instructional activities*

2.2-Prepare Small modules

- Identify important concepts used to write structured design problem.
- Each module will contain only one concept .
- *E.g. Concept identified in amplifier design is relation between gain and bandwidth*

1 Fringing effect

2.2-Prepare Small modules

- 1.Identify facts to be recalled.
- *Gain calculation and bandwidth calculations are facts to be recalled*

Calculation of effective dielectric constant, dimension of patch and feed position

2.2-Prepare Small modules

- 2.Decide principles to be taught to help students to take decisions.
- Student should know --Product of gain and bandwidth is constant.

maximum power transfer

2.2-Prepare Small modules

- 3.Decide decision steps to be followed.
- Identification of gain as high or low is first step then identification of bandwidth high or low is second step etc

Identify suitable feeding technique, dielectrics

Content of module will be listed as follows

- Facts—
- Principles-
- Sequence of decision steps--

2-2..Learning Objectives

Write learning objectives .

1) *What is learning objective(LO)?*

(LO is specific, measurable performance outcome of student.)

2)How to write LO?

Each step from solution analysis is used to write learning objective.

1.Student should be able to identify and interpret relevant specifications/design goals/design requirements from given open problem.

Example:

- *Students should be able to identify gain is important specification in design of amplifier.*
- *Student should be able to calculate gain of given system*

Use solution analysis step1 - write learning objective

- Student should able to select dielectric based on parametric study.
- Students should able to calculate dimension using formulae.

2-1..Learning Objectives

2.Students should be able to decide important structures like circuits/components/blocks/systems based on specification.

Example:

Students should able to decide number of stages in the amplifier circuit based on gain

Use solution analysis step2 -- write learning objective

- Student should able to decide feeding technique.

2-2..Learning Objectives

3.Student should able to sequence decision steps to structure open problem.

Example-

Student should calculate gain first and then decide circuit to satisfy gain requirements.

Use solution analysis step3 -- write learning objective

- Students should able to calculate feed position using formulae.

2-2..Learning Objectives

4. Student should able to write structured statements contain all specifications and structures.

Example :

Students should able to write statement like design of two stage /single stage BJT/FET amplifier for given gain and bandwidth

Use solution analysis step4 --- write learning objective

- Student will able to write statement like Design of inset fed Rectangular Microstrip antenna for WLAN application..

2. 3.Write instructional activities

- For each learning objective write instructional activities.
- Steps to write instructional activities are given .

2.3.Write instructional activities

- Learning objective 1

1.Student should able to identify relevant specifications/design goals/design requirements from given open problem.

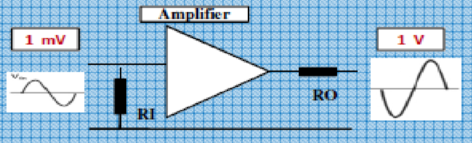
A)Write concept clarification Question (CCQ) as per given guidelines

2-3-A.-Write CCQ

CCQ will contain

- *Question to test student's interpretation of design goals/specification/design requirements.*
- *Answers--Multiple plausible answers with one correct choice.*
- *Feedback –*
- *a) Explanation related to reasoning for why the answer is wrong*
- *b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .*
- *c) Feedback for correct answer also will explain why selected answer is correct(reasoning for correct answer)*

Example



What is gain of amplifier given in the set up?

10	100	1000
Gain of the amplifier is calculated as Gain=Vout/Vin.	Gain of the amplifier is calculated as Gain=Vout/Vin.	You are right! Gain of the amplifier is calculated as Vout/Vin=1V/1mV.

- Write CCQ for your Learning objective 1
- Which parameters are required to be considered for designing an antenna.

2..2.Write instructional activities

- Learning objective 1
- *1.Student should able to identify relevant specifications/design goals/design requirements from given open problem.*

B) Write Decision Making Task Question(DMTQ)

2..2-B.Write DMTQ

DMTQ will contain

- *Question to identify which is relevant specification from given set of specifications.*
- *Answers--Multiple plausible answers with one correct choice.*
- *Feedback –*
- *a) Explanation related to reasoning for why the answer is wrong*
- *b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .*
- *c) Feedback for correct answer also will explain why selected answer is correct(reasoning for correct answer)*

Example

For the given amplifier set up, which of the following specification you will consider while designing the amplifier circuit?

Gain

You are right ! Gain is important specification in amplifier design ,since it can decide number of stages in the circuit and type of active devices in the circuit.

Faithful amplification

Faithful amplification cannot decide the stages or type of devices .It is not useful specification in deciding the circuit blocks and can decide only location of Q point. Try again.

Output voltage

Output voltage is useful to design single stage amplifier but not helpful to decide number of stages .Try again

Write DMTQ as per guidelines for learning objective1

- Which feeding method will you use to reduce losses

2..2.c.Write instructional activities

- For each learning objective develop instructional activity as per the steps given below ------
- Learning objective—solution step1—

c) Add Animation with visual feedback –

This will contain dynamically linked multiple representations.

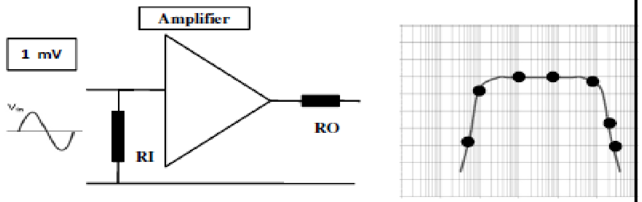
2.2-C.Add Animation

- Select specification which may need either graph/waveform/circuit /blocks/process (representations) for explanation.
- Identify appropriate graph/circuits/waveform/block /process to represent specification.
- Identify parameters to be represented in graph/circuit/block /process.
- Describe relation between selected parameters either using tables or separate slides.
- Animation will contain frame by frame variations.
- In each frame show representations simultaneously.
- Provide start ,stop and pause buttons.
- Animation will explain the specification /design goal/design requirements.

Example

- For amplifier design bandwidth specification is selected, which need graph to represent bandwidth.
- To shown concept of bandwidth we need semi-log paper
- We need gain variation with respect to frequency to show bandwidth.
- We form a table of frequency Vs gain and then plot point on semi-log paper.
- Show animation for each point separately on slides.
- Write actions expected for play, pause and stop button.

Animation will look as shown



To observe frequency response plot click play button

2-3-A.-Write CCQ

CCQ will contain

- *Question to test student's study of primary goals/specification/design requirements.*
- *Answers--Multiple plausible answers with one correct choice.*
- *Feedback –*
- *a) Explanation related to reasoning for why the answer is wrong*
- *b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .*
- *c) Feedback for correct answer also will explain why selected answer is correct(reasoning for correct answer)*

Add animation as per guideline

Select dielectric material ,from the given choice

HIGH DIELECTRIC CONSTANT

Low DIELECTRIC CONSTANT

Add animation as per guideline

Select dielectric material ,from the given choice

HIGH value of height of DIELECTRIC

low value of height of DIELECTRIC

Which formula gives correct dimensions of the patch

Formula will be given student will select proper formula then correct reason for it will be displayed

2..3.Write instructional activities

- Learning objective 2
- *2.Students should be able to decide important structures like circuits/components/blocks/systems based on specification.*
- A)Write DMTQ and INFO Box.

2..2-B.Write DMTQ

DMTQ will contain

- *Question to identify which is better feeding method for the design*
- *Answers--Multiple plausible answers with one correct choice.*
- *Feedback –*
- *a) Explanation related to reasoning for why the answer is wrong*
- *b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .*
- *c) Feedback for correct answer also will explain why selected answer is correct(reasoning for correct answer)*

2.2-A-Write DMTQ&INFO Box

- How to write Question?
- Question to decide important circuit/ block /system/components for given specifications.
- Include multiple representations .
- Answers-Multiple plausible mainly targeting misconceptions of students
- Feedback—

a) Explanation related to reasoning for why the answer is wrong

b) Explanation which can lead students to the correct answer.(but not to tell correct answer) .

c) Feedback for correct answer also will explain why selected answer is correct(reasoning for correct answer) and leading students to next decision step

Example

- **Which of the following circuit combination can provide gain of 1000?**

Single stage BJT amplifier	Two stage BJT amplifier	Single stage FET amplifier	Two stage FET amplifier
Gain of 1000 is considered as high gain and single stage BJT amplifier is not sufficient to provide this gain. Refer Info Box	You are right! Gain of 1000 is high gain and two stage BJTamplifier can provide this gain. Refer info box for more details	Gain of 1000 is considered as high gain .While gain provided by FET amplifier is very low and thus single stage FET amplifier can not provide this gain. Refer Info box	Gain of 1000 is considered as high gain. But FET amplifier is low gain amplifier and two stage FET is not sufficient to provide this gain. Refer Info box

Write DMTQ as per guideline

- **Which of the following feeding method can be used for better performance of the antenna**

Coaxial feed	Microstrip line feed	Aperture feed
Advantages/disadvantges will be written	Advantages/disadvantges will be written	Advantages/disadvantges will be written

2.3.-A-Write DMTQ&INFO Box

- What INFO Box will contain?
- Information which will help students to take decisions.
- Example

INFO BOX

Maximum gain of single stage BJT amplifier is approximately =100
Maximum gain of single stage FET amplifier is approximately =10
Gain of two stage amplifier is=gain of first stage*gain of second stage

Write info box as per guideline

INFO BOX

Advantage of all methods to help students to slelect

2..3.Write instructional activities

- Learning objective 2
- *2.Students should be able to decide important structures like circuits/components/blocks/systems based on specification.*
- B)Include Variable manipulation

2.3-B-Write VM

- For writing VM activity TELE-EDesC writer need to follow following steps
- 1-Identification of part of solution analysis.
- 2-Writing VM activity.

2.3-B-step1-Write VM

- Identification of solution part—
- VM can be written for all of the following---
- Part of solution analysis in which different ideas need to be explored.
- Part of the solution in which students need to connect different specifications /design requirements/design goals to each other and then take decisions in design process. Thus VM will be designed based on concepts required to take key decisions in design process.

How to write VM?

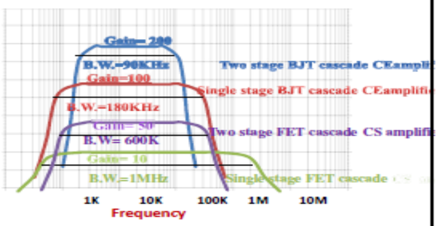
- How to add variable manipulations?
- *Include variable manipulations such that students should be able to change input variables or parameters or conditions within system and can immediately observe corresponding changes in the output.*
- *Show Different representations simultaneously*
- *Add buttons to move forward,backward,increment ,decrement.*
- *Show Separate frame for each variation.*
- *TELE-EDesC writer need to select range depending on design requirements*
- *Feedback box to explain the effect of variations or follow up question answer feedback to test student's understanding from animation/variable manipulation etc.*

- Example--Select part of solution for VM----- Frequency response of different circuits is selected which need different circuits for different frequency responses and also convey concept of gain bandwidth product

2.3.-B-Write VM

Select given combination of circuits and observe frequency plots

- Single stage BJT CE amplifier
- Two stage BJT cascade CEamplifier
- Single stage FET CS amplifier
- Two stage FET CS cascade amplifier



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Write Variable Manipulation(VM)

- Here antenna with different combination of dielectric material and feed method can be given and students can be asked to select any for given application

2.3.Write instructional activities

- For each learning objective develop instructional activity as per the steps given below ------
- Learning objective—solution step3—

Decide overall sequence of decision steps.

Example--

Write sequence of decision steps

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Date:

IIT Bombay, India Madhuri Mavinkurve