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Teaching research skills for experimental physics in an undergraduate electronics lab

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[This paper is part of the Focused Collection on Instructional labs: Improving traditions and new directions.] We present the pedagogical design and implementation of "ESSENCe": Experimental problem solving using Staging, Scaffolding, Embedded information sources, iNstruments, and Collaboration. Research in experimental physics requires problem-solving skills that include designing investigations, developing instrumentation techniques, troubleshooting, planning data analysis, and evaluating experimental outcomes. Most of these skills can be taught at the undergraduate level but are unfortunately skipped in traditional cookbook-recipe style labs. Since many physics experiments require electronics, the ESSENCe pedagogy presented here has been developed in the context of undergraduate electronics laboratory courses. The goals of ESSENCe labs are to help students apply their theoretical knowledge of electronics to hands-on open-ended experiments, understand properties of physical systems and limitations of measurements, and to learn how to work with sophisticated instruments used in experimental research. ESSENCe emphasizes collaboration with peers and teaching assistants. This paper presents the results of ESSENCe implementation in a sophomore undergraduate analog electronics lab of 45–60 students over multiple years in a top-ranked technological university in India. A mixed methods study was conducted to analyze students' development of experimental problem-solving skills through repeated measures of performance on experimental tests and video analysis of students working on the experiments. We found statistically significant improvement in students' experimental problem-solving skills over the course of a semester. The study also analyzed students' perceptions about the benefits and challenges of the open-ended collaborative lab.

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I. INTRODUCTION

Modern physics experiments rely on electronics for a variety of purposes. Some experiments use electronics to capture signal measurements of physical variables [1], others use it for controls and automation [2]. In addition to conceptual knowledge of electronics, a practicing physicist requires experimental problem-solving skills such as designing experiments, troubleshooting the experimental designs, planning data analysis, and evaluating experimental outcomes. In order for students to develop such mastery, training in experimental problem-solving skills using electronics can be fostered in undergraduate physics and electronics labs.

Recommendations from standards such as the AAPT committee on labs [3] and professional organizations like ABET [4] have reiterated that undergraduate physics labs should address the goals of designing experimental investigations, evaluating experimental data, and developing the ability to work in groups. Traditional undergraduate labs typically have instruction "manuals" that emphasize following given procedures without delving into the interplay between the theory and practice [5], or providing an avenue for the physical realization of concepts learned in a theory course [6]. In a basic electronics lab, this translates to an experience that is limited to building standard circuits and verifying established principles by following given procedures. Students lack the opportunity to engage with the experiment, make plans and decisions regarding the design and analysis [7,8], and construct knowledge [9].

We have designed a pedagogical strategy called "ESSENCe" (Experimental problem-solving using Staging, Scaffolding, Embedded information sources, iNstruments, and Collaboration) for instructional labs to promote experimental problem-solving skills among physics students in the context of analog electronics. Experimental problem-solving skills include the ability to design, analyze, build, and test circuits while using instruments in an expertlike manner. Through this process,

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the students learn to take into account the practical limitations of electronic devices and utilize the potential of testing and measuring instruments. ESSENCe borrows aspects of problem-based learning [10] in an inquiry lab format [11]. The experiments are scaffolded by the instructor with opportunities to discuss with peers and teaching assistants (TAs). Our focus is on improving the application of conceptual knowledge and disciplinary strategies while building experimental design skills applicable to experimental physics problems.

In this article, we review relevant literature on the goals of labs and pedagogical strategies in the context of labs focusing on experimental problem-solving. We describe the theoretical basis of ESSENCe and its key pedagogical design features. We then provide a detailed case study to illustrate the implementation of one ESSENCe lab. We report the findings of a mixed methods study that analyzed students' development of experimental problem-solving skills and their perceptions.

II. RELATED WORK

Undergraduate research experience with legitimate peripheral participation has been proposed as a means of bringing students closer to scientific practices. Undergraduate research experience has been shown to help in developing habits of mind [12–14] and inculcate the practices of experimental physicists. Researchers have articulated goals of undergraduate lab courses that include using models as predictors of real-world behavior, designing or devising experiments, collecting, analyzing, and interpreting data, applying scientific procedures to investigate phenomena and solve problems, effective oral and written communication, working in teams, and learning specific scientific methods, instrumentation, and lab techniques [8,15].

In an electronics lab, in addition to building conceptual understanding, students need to develop new disciplinary strategies pertaining to design, testing, measuring, and troubleshooting while engaging in reasoning and sense-making. At the same time, students face challenges at several levels. This includes grappling with their evolving conceptual knowledge (such as conceptual models for electronic circuits), new disciplinary strategies [16] (heuristics and tacit knowledge), and unfamiliar instruments to be mastered and used to analyze, interpret, and troubleshoot circuits. Research studies in the past two decades have aimed to address some of these goals and challenges using various pedagogical strategies. Inquiry methods have been used to improve the specific experimental problem-solving skill of formal circuit analysis [17]. A pedagogical strategy of disassemble/analyze/assemble has been shown to motivate and improve student perception of learning of design skills [18]. Troubleshooting skill development has been addressed in a lab by adopting a socially mediated metacognition framework [19] and model-based reasoning [20]. Investigative Science Learning Environment (ISLE) [21] encourages students to construct physics knowledge and develop scientific abilities. Learning in ISLE occurs when students design their own experiments and reflect upon their work [12]. A junior-level electronics course [22] fosters the development of students' scientific practices by guiding them through a process of comparison, revision, and prediction.

Practical skills addressed in labs include improving collaboration skills [23], affinity toward electronics [23–25], communication including reasoning skills [12,26,27], and equipment mastery [27]. Circuit-X [27] lab is built around the ideas of discovery, design, and delivery in the context of analog electronics. Students work in groups of three to identify the topology and values of an unknown circuit by designing relevant tests, working with the equipment to conduct tests and interpret data, and preparing a report and presentation. In addition, studies in electronics labs have investigated different modes such as virtual labs [28], kit-based labs [29], computer-assisted remote or distributed lab [30], and courses that blend lectures and experiments [31].

Modeling is an important scientific practice in a laboratory course. Modeling comes to the fore when students are expected to design circuits at limiting conditions or when students need to take into account the interaction effects of the different circuit elements to explain discrepancies between actual and expected behavior. Ríos *et al.* [32,33] have investigated modeling tasks in the analog electronics lab and identified five subtasks, namely, constructing models, making measurements, making comparisons, proposing causes, and enacting revisions. They observed that when encountering discrepancies, students tend to make many measurements with intermittent comparisons. They perform iterative revisions as a means of understanding the discrepancy. They, however, struggle to propose causes and enact revisions toward resolving discrepancies.

The review of related work has provided pedagogical recommendations to facilitate productive lab experiences and develop students' experimental problem-solving skills. These studies highlight the role of scaffolding, peer collaboration, opportunities for design, and practice and reflection on establishing connections between concepts, data collection, and interpretation. The focus of many of the labs with nontraditional pedagogies is to enable students to apply their knowledge of analog circuits in designing or analyzing real-world systems. The value of this format is in engaging students and grounding their knowledge in real-world projects. Students reported challenges such as investigation of the nuances of circuits at limiting conditions, reconciling unexpected outcomes, and struggle to redesign [32,33] underline the importance of exposure to such lab tasks and highlight the requirement of providing necessary scaffolds. Holmes and collaborators [34,35] discuss varying levels of open-endedness that are incorporated in nontraditional labs. The elements of open-endedness provide students with opportunities to make decisions, act on the decisions, reflect on the outcomes, and enact modifications to the experiments iteratively.

The ESSENCe pedagogy and corresponding lab that we describe in this paper address the vital aspect of equipping Physics majors with sufficient experimental problem-solving skills in electronics so that they get a deeper understanding of electronics from a bottom-up approach and can apply their constructed knowledge to advanced problems in experimental physics. We describe the pedagogical strategy and implementation with an illustrative case study and analyze students' development of problem-solving skills.

III. COURSE OVERVIEW AND GOALS

The basic electronics lab is offered to Engineering Physics undergraduates entering their sophomore year. In this semester-long lab course, students meet once every week for 3 hours. In addition, they are given prelab reading and assignments on the Moodle learning management system to prepare for the lab activities. Eight foundational experiments are covered in this lab course. The topics include voltage and current sources, active electronic elements—diode, diode characteristics, transistor characteristics, common emitter (CE) amplifier, CE amplifier with feedback, emitter follower as a transistor current amplifier, and push-pull amplifier. Students prepare for each of the lab session using the prelab assignments provided by the instructor. The prelab assignments include reflection or assimilation questions and reference material related to the lab experiment.

The goal of the lab is to help students integrate their theoretical knowledge of electronics, their understanding of properties of physical systems, limitations of measurements, and use them as tools for electronics experiments as illustrated in Fig. 1. The instruction design of the lab focuses on developing students' ability to

- Design experiments and devise procedures to solve problems of electronic design and measurement,
- Analyze experiment designs to reconcile inconsistencies or troubleshoot the experiment design,
- Make expertlike use of sophisticated instrumentation for basic electronics.

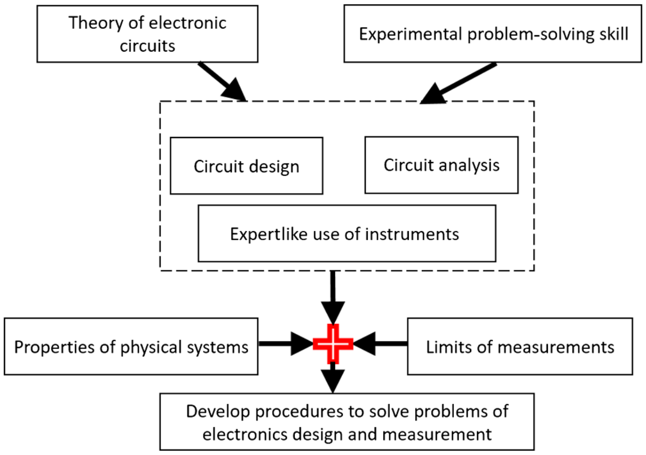


FIG. 1. Lab course goals.

The lab assignments encourage students to investigate circuit behavior in detail, including aspects of how behavior of individual components in a circuit affects the overall functionality of a circuit, how signals and operating conditions influence circuit behavior, how the topology of circuits affects circuit functionality, why real circuits behave differently from theoretical expectations, and how the inclusion of test instruments modify circuit operations.

IV. THEORETICAL BASIS AND PEDAGOGICAL DESIGN

At the core of the ESSENCe labs is an experimental investigation of a circuit design or circuit analysis problem, for which students have to devise a solution. To solve the problem, students engage in design as well as analysis activities. Typically, the experimental investigations are staged so that students understand the problem context and connect it to their conceptual knowledge. In the design activities, students figure out how to meet the design specifications by choosing a circuit configuration, identifying the relevant mathematical models, and calculating component values. They also plan in advance the type of signals to apply as inputs to the circuit, and the measurements necessary to test the design. In analysis activities, students investigate discrepancies between theory and experimental observations, examine the operation of circuits at limiting conditions, and propose approaches to overcome the circuit limitations. Borrowing from the 4C/ID model [36,37], the experimental investigations are broken down into simpler tasks, sequenced from simple to complex, and have high variability of practice. This ensures that students integrate recurrent and nonrecurrent skills and knowledge including domain-specific models, cognitive strategies, and schemas.

No explicit instructions are provided on how to solve the lab assignment. However, the tasks are scaffolded with reflection questions and hints that adopt the problematizing and structuring mechanisms of scaffolding [16]. Pertinent information such as extracts from component data sheets, governing equations, and practical usage techniques are provided to the students when necessary. This ensures that students can focus on the key task and are not distracted searching for information [8]. Also, such supportive information helps learners connect previously acquired knowledge to the newly presented knowledge [36]. Just-in-time information ensures that the student's working memory has access to the information when performing the task. Students maintain a detailed experiment log in which they record their design, observations, and reflections.

Students collaborate in small groups while solving the experimental problem. Productive academic talk [38] occurs when peers collaborate, contribute to enhanced explanatory responses, reasoning, problem-solving, and learning. Learning amidst productive academic talk happens when students ask precise questions and persist in finding answers by listening to each other, challenging ideas, seeking evidence, generating rebuttals, justifying and validating their conjectures, recognizing their own misunderstandings, and building connections with their prior knowledge. In ESSENCe labs, the instructor and TAs facilitate the experimentation process by evaluating in real time the students' approach to tasks (each subtask is graded *in situ*). They provide critical feedback through question prompts to encourage reflection and discuss the implications of students' approach. Resources in the form of research-grade measuring instruments and reference material as a part of prelab activity are provided to the students.

Figure 2 illustrates the core elements of ESSENCe pedagogical strategy used in the lab. The key pedagogical design elements are as follows:

- **Staging activities**—Staging activities are short well sequenced, structured investigations that are typically conducted at the beginning of an experiment. They are designed to help establish the background and premise for the open-ended experiment. In staging activities, students connect their background knowledge and investigation techniques to the experiment at hand. The benefits of staging activities include motivating students by either eliciting their curiosity or capturing their interest and making the investigations more accessible [39].
- **Embedded information sources**—Presentation of task-relevant information in chunks before and during practice, has been shown to have an effect on cognitive effort, information assimilation, and subsequent usage in transfer tasks [40]. The information provided to the students in the lab is restricted to being timely, necessary, and sufficient. Typically, it includes relevant device parameters and sections of component datasheets where necessary. Practical hints on building circuits, cause-effect reasons for following good practices in building circuits, choosing components, connections, and testing methodologies [39] support students in developing hands-on experience.

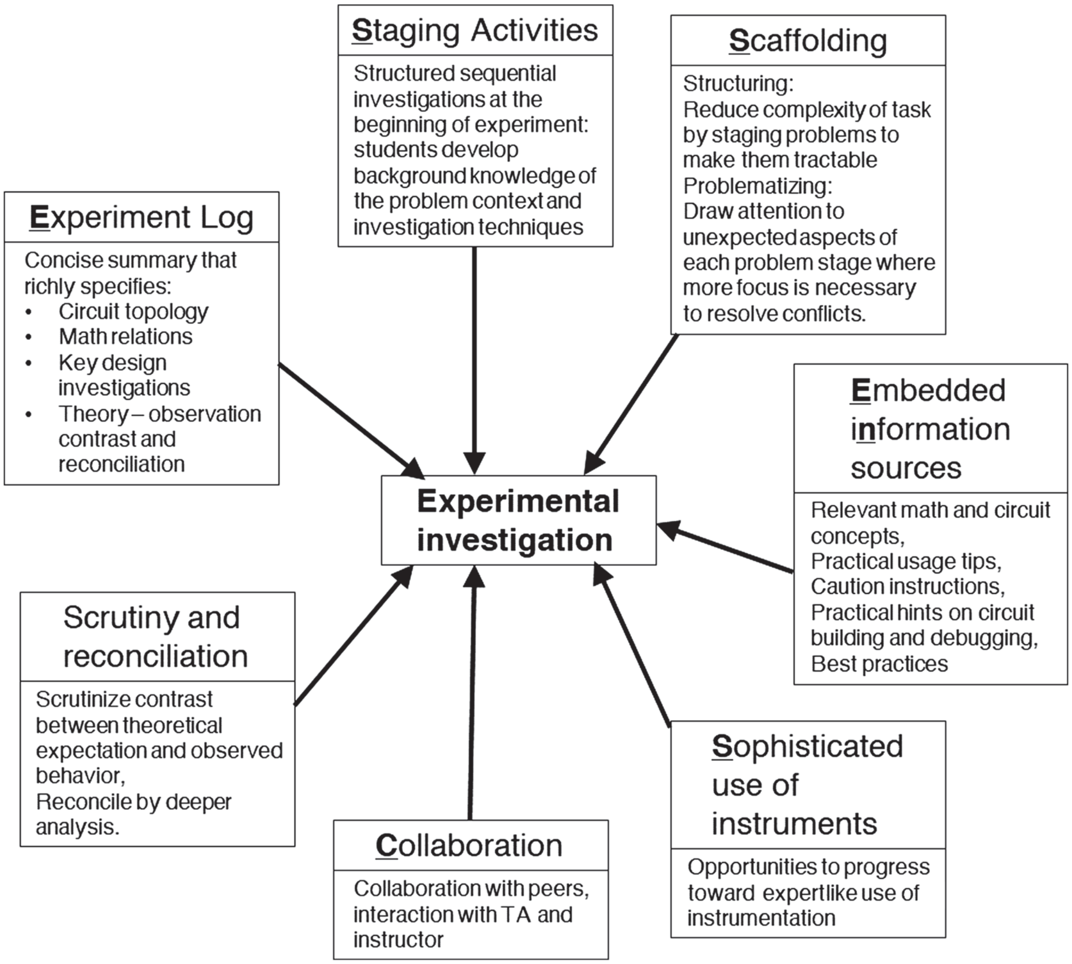


FIG. 2. Elements of ESSENCe pedagogical strategy.

- **Scrutinize and reconcile**—Theory courses often describe ideal states or use approximate models to convey behavior of electronic devices. While the theory is important to understand concepts, it is essential for students to be aware of behavior of devices when used in a practical circuit. They need to be able to identify where and when a circuit's behavior differs from expectation [41], what causes the difference, and if possible how to minimize such differences. In the process of scrutinizing the circuit, locating the contrast between theory and observation, and reconciling by investigating different factors that contribute to the contrast [42], students build a strong conceptual model. Additionally, they develop an operational understanding of electronic components and avoid thinking locally and sequentially while analyzing circuits [43].
- **Scaffolding** via complementary mechanisms of structuring and problematizing [16]—Scaffolding is a mechanism by which students are assisted in different ways so as to succeed in tasks that would otherwise have been beyond their individual capability. Scaffolding in the form of structuring reduces the complexity of a problem by hand-holding the students through conceptually decomposed steps such that students arrive at the right solution. Problematizing on the other hand, deliberately introduces complexity to the problem, thereby forcing students to engage with the problem. In doing so, students learn new strategies to tackle the complex problem and learn to appreciate nuances in the experiment that may be overlooked.
- **Collaboration**—When students interact with one another, they engage in discursive activities such as negotiation, argumentation, reasoning, questioning, and reflecting on their experiences [44]. In the process, students explore and construct knowledge by collective thinking, knowledge pooling, and shared sensemaking, leading to conceptual change [45]. Collaboration is therefore a powerful mechanism for learning. Studies have shown that collaboration in the lab enables students to collectively strategize about different aspects of the experiment such as measurements to perform, troubleshoot the circuit, and arrive at a shared understanding of the circuit behavior [19]. Interaction during collaboration encourages students to use discipline-specific language so as to effectively convey their point of view. In this process, students develop their discipline-specific language skills.
- **Sophisticated usage of instruments**—Effective use of test and measuring instruments in the lab is a key skill that experts possess. One of the main goals of ESSENCe is to help students acquire this skill. Targeting expertlike usage of lab instruments requires the availability of sophisticated instruments such as a digital storage oscilloscope, arbitrary function generator, power supply, and a digital multimeter. Since the lab format encourages collaboration, much of this equipment can be shared among student groups. Ample time is provided in the initial sessions of the lab to enable each student to learn all features of the equipment on their desktop. The lab consists of open-ended tasks with scaffolding questions that prompt students to explore the instruments aiming for eventual expertlike usage. The TAs need a high level of training to guide the students, facilitate discussions, and evaluate their performance.
- **Experiment log**—This is a rich practical resource created by students in response to the assignment questions. Its creation and maintenance is an important aspect of scientific documentation. It contains elements of experimental design such as *predicted* circuit response, relevant mathematical relations, key design investigations, observations, conflicts between predictions, and observations followed by reconciliation with arguments. The experiment log therefore forms a rich summary of the students' lab experience and learning. ESSENCe uses the submitted experiment logs as the main basis for students' performance evaluation in addition to in-lab demonstrations. Hence, the students are incentivized to make exhaustive experiment logs. Scientific documentation in labs requires explicit training [46]. Scientific documentation in labs requires explicit training which ESSENCe provides.

V. ESSENCE LAB IMPLEMENTATION: ILLUSTRATIVE CASE STUDY

This study was conducted over two iterations of the lab course in the Physics department at the Indian Institute of Technology Bombay in Mumbai, India. In the first year, researchers from the educational technology program (S. N. and S. M.) collaborated with the instructor and teaching staff (including P. S. and N. P.) to understand the lab goals, how the instructor had designed the lab assignments, and the interactions during lab implementation. This interaction was used to design the details of the research study. The second year focused on data collection and analysis where we evaluated students' development of experimental problem-solving skills while they experience the ESSENCe intervention. Students in this course have completed standard first-year courses in mathematics, electricity and magnetism, basics of quantum physics as well as a theoretical course on basic analog electronics that includes Kirchoff's laws, basic circuit analysis, and analog devices such as diodes, transistors, etc. The assignments in this lab course were built upon the concepts covered in the theory course. To illustrate the application of the ESSENCe pedagogical design, we provide a walk-through of the first lab assignment on the topic of diodes and their applications. We also provide instances of interactions among students and between students and the instructor team.

In the initial orientation sessions of the lab, students are given an introduction to the instruments set up on their lab tables: a two-channel digital storage oscilloscope (DSO), an arbitrary function generator (AFG), a two-channel power supply (PS) and a digital multimeter (DMM). They are given ample training and practice time to learn how to operate these instruments.

The lab assignment on diodes in this case study is structured into three exercises. The exercises are of increasing levels of difficulty, incrementally building up concepts required for the final solution [an example of *Staging activities* in Fig. 2]. Students work in groups of three, they are encouraged to discuss aspects of the experiment. Each exercise asks several open-ended questions, whose answers the students record in their individual experiment logs. The experiment logs are submitted at the end of the session. The logs are used as part of the assessment, along with an evaluation of each student's ability to build and demonstrate working circuits in the lab session.

In the prelab assignment for this experiment, students were given reading material relevant to diodes and their applications and asked to answer a quiz on Moodle. TAs grade the submitted responses to the quiz *before* the lab session to gauge students' level of preparedness.

Exercise 1: Students are given circuit diagrams shown in Fig. 3. They are provided information regarding the threshold voltages of the diodes, $V_t = 0.5$ V, and maximum current allowed through the diodes D1 and D2, $I_{\max} = 10$ mA [an example of *Embedded information* in Fig. 2]. The value of the resistance is not specified. Students are asked to analyze the circuit and write their answers in their log: the question asks them to predict and sketch the expected voltage V_{out}. Question prompts are provided [these form the *Scaffolding* indicated in Fig. 2]. A typical scaffolding question is "What is the conduction state of D1 and D2 in the positive/negative half cycle of V_{in}?" TAs evaluate the provided answers in the lab and check that students understand the concepts required.

Students are then asked to build the circuit on their breadboard. Passive components such as resistors, capacitors, etc. required for performing the experiments are kept in a central storage area. Students must go and pick up the components after calculating the required values. Below is an interaction between two students s1 and s2 as they work through the analysis to determine V_{in} and R, which exemplifies the *Collaboration* aspect of ESSENCe pedagogy (Fig. 2).

s1: $I_{\max}$ of the diodes is the only parameter specified. How do we calculate R?

s2: Another thing is not specified: the amplitude of V_{in} so the circuit has a voltage, an R and we must set the current, so it must be something to do with Kirchoff's Voltage law—once the diode is conducting, it's basically short-circuited right?

s1: There will be a 0.7 V voltage drop across it.

s2: Yes okay, so if we take $V_{\text{in}} > 0.7$ V, let's say $V_{\text{in}} = 1$ V, we want to make sure $(V_{\text{in}} - 0.7\ \text{V})/R < I_{\max} = 10$ mA

s1: Okay so let's take $R = 100\Omega$—that will give us worst case $I_D = 3$ mA

After having thus completed the circuit design with a full understanding of how it should behave, they find the hands-on circuit building and verification rather straightforward. But upon measurement of V_{out} (Fig. 4), they immediately realize something is not quite right:

s1: V_{out} doesn't look clipped as I expected

s1: No wait, it's fine: look at the scale on the DSO. The positive part clips at 0.7 V and the negative part does clip at -0.7 V

s2: Yes the other half goes to 1V so it looks mostly symmetrical. I guess we need to increase V_{in} to get a nice half sine wave like we expected

s2: But then we need to increase R too, right? Let's just pick a round number $V_{\text{in}} = 10$ V and use $R = 1k\Omega$—remember the

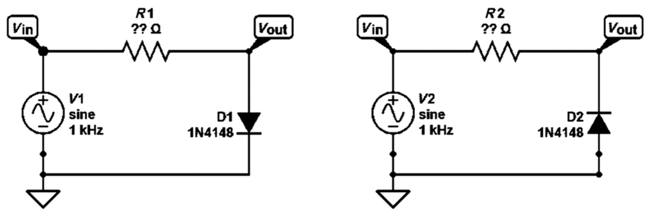


FIG. 3. Circuit diagrams for exercise 1 given to students for analysis, before building the circuit. Current limit $I_{\max} = 10$ mA on D1 and D2 and $V_t = 0.7$ V are specified, but the value of R and the amplitude of V_{in} are not given.

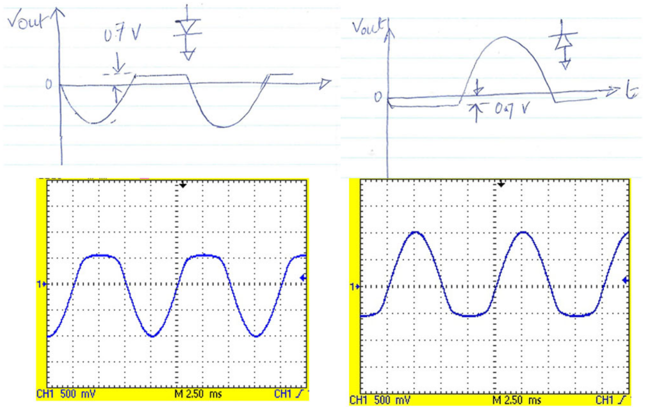


FIG. 4. Sketch of predicted V_{out} drawn by a typical student (upper row) for the two circuits of exercise 1 shown in Fig. 3. Corresponding waveforms observed in the circuit with $V_{\text{in}} = 1V$ (lower row).

teacher told us to use standard values of R, C?

Such *scrutiny and reconciliation* is a key aspect of the ESSENCe pedagogy (Fig. 2).

In exercise 1, students learn by discussing how to apply known and basic laws (Kirchoff's voltage law and Ohm's law) to a problem. In a simple context, they get a sense of achievement from having a predictive understanding of what to expect after building the circuit and are able to tune the parameters to test their prediction.

Exercise 2: Students are asked to exchange the location of the diode and resistor in the circuit of Fig. 3 and predict the V_{out} they expect to observe. They were further asked to relate it to the behavior of any other circuit they had studied in the theory course. In the following discourse, s1 and s2 attempt to make sense of the observations.

s1: what difference does it make if the current limiting resistor comes before or after the diode?

s2: let's see what happens to the positive diode clamp. Yes that looks like all the negative halves of the sine V_{in} are removed. So it's like a negative clamp if the diode comes before the R

s1: oh, and for the negative diode clamp all the positive halves of the sine V_{in} are removed

s2: so basically both circuits become half-wave rectifiers

s1: yes but I've never seen a negative half-wave rectifier. It would give a negative dc voltage after filtering right? The positive half-wave rectifier would give the standard positive dc voltage

Students are thus able to extend their prior knowledge and reconstruct a well-learnt idea. In their analysis (which was tractable after the groundwork done in exercise 1) they are able to "discover" something new—a method of making a negative dc voltage by converting a negative diode clamp to a half-wave rectifier.

Exercise 3: Students are asked to expand on the ideas in exercises 1 and 2 and design a full-wave rectifier using four diodes. They have previously learned that a bridge rectifier produces an output whose value is the absolute value of V_{in} (always positive, for both positive and negative halves of a sine wave). Several questions such as the ones posed in examples below probe their understanding in detail, and they are required to articulate their responses and reasoning in the experiment log. Taken together, these emphasize the *scaffolding* and *experiment log* aspects of ESSENCe pedagogy (Fig. 2).

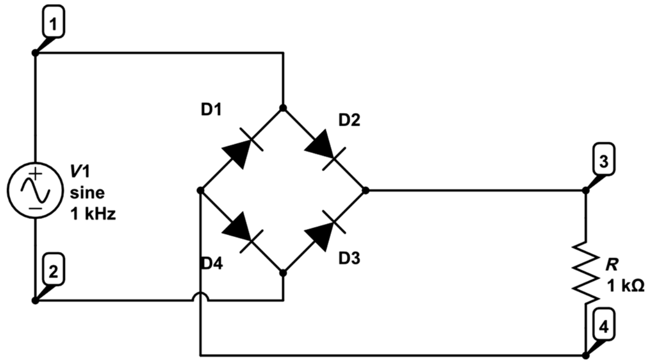


FIG. 5. Expected solution of exercise 3—design and test of a bridge rectifier circuit.

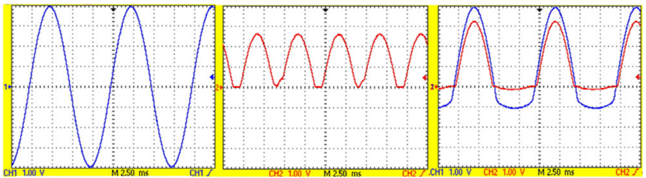
1. Q: Include all the relevant resistors to limit current through the diodes in conducting state. How many resistors are needed? *Mark clearly in your design diagram four points between which you will connect and measure V_{in} and V_{out} in your circuit.* Make a sketch of the predicted waveforms.

   Students are able to recall the textbook four diode bridge rectifier circuit (Fig. 5) and draw it in their experiment briefs. Some choose to put four R's in their experiment briefs to protect each diode—this is acceptable as such. The TAs point out to the students that really only one R is required. With practice from the earlier exercises, most students are able to specify the four points [1,2,3,4] in Fig. 5 between which they expect to measure V_{in} and V_{out}, respectively.
2. Q: Connect the bridge rectifier circuit as per your design on your breadboard, using the required number of diodes and current limiting resistors.

   Students have had sufficient practice in the earlier exercises (identifying the anode and cathode of the diode). They already know the required R value for current limit. All students connect the circuit on their breadboard.
3. Q: Since the bridge rectifier is a bigger circuit requiring more parts than in the earlier exercises, it is a good idea to verify its operation end-to-end. Measure V_{in}—display it on Channel 1 of your DSO.
4. Q: Measure V_{out}—disconnect V_{in} and display V_{out} on Channel 2 of your DSO. For questions 3 and 4, record your observations carefully in your experiment log including the amplitudes of observed waveforms.

   Students perform these step-by-step checks of input signal reaching the circuit and correct output produced as per the expectation and record their observations as shown in Fig. 6.
5.
   (a) Q: To verify the full-wave rectification, measure *both* V_{in} and V_{out} together—display both voltages on Channels 1 and 2 of your DSO. Record the amplitudes of your measurements carefully.

   Students observe the waveform shown in Fig. 6(c). They are puzzled at the unexpected observation. V_{in} and V_{out} have each been individually verified [Figs. 6(a) and 6(b)]. Yet when observed together on two channels of the DSO,



(a) V_{in} measured (Channel 1 in blue)

(b) V_{out} measured (Channel 2 in red)

(c) V_{in} (blue) and V_{out} (red) measured at together

FIG. 6. Observations made by students for the circuit assembled as per Fig. 5. (a) V_{in} measured alone on Channel 1 of DSO (b)V_{out} measured alone on Channel 2 of DSO (c) V_{in} and V_{out} measured together on Channels 1 and 2 of DSO.

both V_{in} and V_{out} appear to be half-wave rectified or clamped above -1 V [Fig. 6(c)]. Several question prompts are provided in the assignment sheet to guide them through solving this puzzling observation.

(b) Q: Examine the markings on the output terminal of the AFG from where you connect V_{in} to your circuit and your DSO probe connections at the DSO front panel. What is the ground reference for each of these signals? After identifying the ground reference for V_{in} and V_{out} put labels with the ground symbol at relevant points in your circuit design. Such *sophisticated use of instruments* is an important aspect of ESSENCe pedagogy (Fig. 2)

In textbook diagrams, students have learned of a bridge rectifier exactly as shown in Fig. 5 which has no ground reference. However, the AFG output terminal and the DSO front panel connections indicate a ground symbol around the outer shell of the cable connector. There is substantial discussion among students and the TAs on the nature of coaxial cables and BNC connectors. The AFG cable has a BNC connector at the AFG, and two crocodile clips colored red and black reaching the breadboard. The DSO probe similarly has a probe tip and a flexible ground wire terminated in a crocodile clip. All students converge on labeling points [2] and [4] in Fig. 5 as ground.

(c) Q: Use the ground reference voltages inferred in the previous question, to evaluate the ON or OFF state of each diode in each half cycle of V_{in}. Accordingly, give an overall explanation of the behavior observed in a full wave bridge rectifier circuit when both V_{in} and V_{out} are measured simultaneously.

This is an analysis question at the end of an experiment. Students are required to write answers in their logs without discussion. The students connect the observations with their earlier work with diode clamps. The following scaffolding subquestions are provided to guide them to the correct understanding and enable evaluation.

Q5c.1: What is the role of diode D4 in the circuit when both V_{in} and V_{out} are measured simultaneously?

Q5c.2: In each half cycle, determine the ON or OFF state of each diode.

Q5c.3: Connect the behavior of this bridge rectifier circuit with earlier single-diode applications in this session. What is the effective behavior of the circuit in each half-cycle?

The staging exercises asking the student to predict the expected results of an experiment based on theoretical concepts are an essential component of ESSENCEe. It requires them to plan ahead for the measurable quantities in the circuit once they finish building it on their breadboard. In later advanced assignments with complex circuits, it becomes important for the student to have a clear understanding of how each subcircuit is expected to behave. Before the student proceeds to circuit assembly, TAs evaluate the predictions in real time and correct mistakes where required. In assignments involving complex circuits, they are encouraged to build up the circuit piecemeal, testing each subcircuit to validate its functionality before connecting the whole thing together. This guards against student frustration upon not seeing the expected final result from a complex circuit that they may have spent significant time building on the breadboard.

VI. RESEARCH METHOD

A. Research questions

In this study, the development of experimental problem-solving skills has been operationalized to include students' performance measured by three criteria: circuit analysis, circuit design, and expertlike usage of sophisticated instruments. We developed rubrics to evaluate circuit design and circuit analysis skill. We analyzed video data of in-lab student activities to look for episodic evidence of expertlike usage of instruments. Our research questions (RQs) are as follows:

1. To what extent do students develop experimental problem-solving skills while they experience ESSENCe labs?
2. What are student perceptions about the lab?

B. Participants

Study participants were second-year students in a 4-year engineering physics undergraduate program. Admission to the undergraduate programs in our institute is based on a highly competitive entrance exam with an emphasis on problem-solving. Students had prior conceptual knowledge of basic analog circuits from the theory course. A total of 45 students were enrolled for the lab course, of which 4 students were female and 41 students were male (this is a

TABLE I. Summary of data sources, instruments used and analysis methods.

Research question	Assessed variable	Data source	Instruments	Analysis method
1	Ability to analyze circuits, Ability to design circuits	Baseline-pretest, Pretest and Posttest scores	Rubrics to evaluate performance in: (a) Circuit analysis and (b) Circuit design	Two-way repeated measures ANOVA to establish statistical significance followed by *post hoc* test to compare pair-wise means.
	Expert-like usage of test and measuring instruments	Video recording of in-lab activities taken during multiple lab sessions		Episodic evidence from video records of actual lab activity.
2	Student perception of the lab	Responses to perception survey questionnaire	Perception survey questionnaire comprising of 5 point Likert scale questions and open-ended questions requiring descriptive answers	Thematic analysis of student responses.

typical gender distribution for this program). The course included four TAs who were either graduate students in experimental physics or senior undergraduates with a strong mastery of electronics lab skills.

C. Data sources and instruments

We used a mixed methods research approach [47] combining quantitative instruments with qualitative research techniques. Data sources included repeated tests where students solved experimental problems, video recordings from multiple lab sessions, and a questionnaire on student perceptions. Table I summarizes how the various data sources were used to answer the research questions.

The baseline, pretest, and post-test question papers used for the assessment are available for download [48]. The baseline test was given in the first week of classes. The pretest was given in week 4 after the students had gained some familiarity with concepts of transistor circuit design. The post-test was given as the final exam at the end of the semester. All the tests were open ended and similar in structure to the assignments that students performed in the lab. However, the tests contained fewer scaffolding questions, and students were not allowed to interact with peers during the tests. Thus, the test performance was a reflection of individual skill. Numerical scores of the pretest and post-test counted toward the course grade. These scores were based on conceptual understanding, correct calculations, and working circuit demos. In addition, an independent rubric-based scoring of the baseline, pretest, and post-test was done by the researchers for the analysis in this study using the parameters listed in Table II and Sec. VI C 1.

TABLE II. Sample criteria in rubrics. The performance levels are indicated in the column headings along with the corresponding numerical scores. Other criteria are listed in Sec. VI C 1.

Criterion	Target (3)	Acceptable (2)	Needs improvement (1)	Missing (0)
A1 (related to circuit analysis): Analyze how functionality of the circuit is affected by various components in the circuit	The student identifies role of a component, its relationship with other components, and its role in circuit operation accurately.	Most of the aspects of the circuit functionality and each component contribution are identified. Some minor points are missing.	Analysis of each components' effect on circuit functionality is incomplete.	No attempt made to analyze effect of components on circuit functionality.
D1 (related to circuit design): Translate requirements to appropriate solution by applying relevant concepts	The student is able to identify the relevant concept to meet the required specifications and arrive at appropriate solution.	The student is able to identify most of the relevant concept to meet majority of the required specifications and arrive at acceptable solution.	Identification of relevant concepts to meet required specification leading to solution is incomplete.	No attempt has been made to identify relevant concepts to meet required specification.

The students wrote responses to the same set of questions and the responses were scored twice, independently and on different sets of criteria—once by TAs for course grades (for the pretest and post-test) and all three separately by the researchers for the analysis in this study. The questions in the baseline test were not used for course grades, and students got participation credit only.

1. Rubrics

Rubrics were designed to evaluate students' circuit analysis and circuit design skills. The criteria in the rubrics were abstracted from the course goals and instructor input. The content of the rubrics was validated by three subject matter experts. Two of the experts had more than 10 years of teaching experience in electronics and had previously taught analog electronics labs. The third expert was associated with the lab course and participated actively as a teaching staff during the lab sessions. Each of the rubric criteria had four performance levels and each level was mapped to a numerical score for quantitative analysis: Target (score 3), acceptable (score 2), needs improvement (score 1), and missing (score 0). The six criteria in circuit analysis are as follows:

- A1: Analyze how the functionality of the circuit is affected by various components in the circuit.
- A2: Identify necessary and relevant mathematical relations between various dynamic quantities and parameters in the circuit.
- A3: Apply relevant mathematical relation to determine current and voltage at different locations in the circuit based on the mode of operation.
- A4: Analyze how the performance of the circuit changes when some components of the circuit are modified [component change includes removal, addition, change in value, change in nature of input, and change in operation conditions].
- A5: Analyze and explain the discrepancy between expected behavior (from theory) and observations on the assembled circuit.
- A6: Explain behavior of the circuit by linking it to theory and operational setup.

The rubric to evaluate the ability to design circuits has five criteria:

- D1: Translate requirements to appropriate solution by applying relevant concepts.
- D2: Suggest and justify chosen solution using theory.
- D3: Make suitable assumptions while selecting solution.
- D4: Come up with a circuit topology that satisfies the specifications and draw it using a circuit diagram or block diagram.
- D5: Compute component values using relevant mathematical formulas.

Sample rubrics criteria for circuit analysis (A1) and design evaluation (D1) are shown in Table II. To establish interrater reliability of the rubrics, two independent raters rated a randomly selected subset ($n = 5$) of student responses to the pretest. Interrater reliability for five criteria of analysis of circuits and five criteria of circuit design was established by calculating Cohen's κ [49]: $\kappa_{A1} = 0.8$, $\kappa_{A2} = 0.76$, $\kappa_{A3} = 0.8$, $\kappa_{A4} = 0.78$, $\kappa_{A6} = 0.79$, $\kappa_{D1} = 0.81$, $\kappa_{D2} = 0.82$, $\kappa_{D3} = 0.77$, $\kappa_{D4} = 0.81$, $\kappa_{D5} = 0.79$. The criterion A5 pertaining to investigating discrepancy between expected and observed outcomes is not reported as some of the tests did not have questions pertaining to this.

2. Perception survey questionnaire

A survey questionnaire was developed to capture students' perceptions of the lab. The questionnaire contained nine questions on a five-point Likert scale and three open-ended questions. The Likert scale questions elicit students' perception of the development of experimental problem-solving skills, their opinions on peer discussions, and their motivation and overall satisfaction in the lab. The open-ended questions ask students to reflect and elaborate on reasons for their preference or nonpreference of the lab format and their perceived usefulness of the lab.

D. Data analysis

The format of baseline, pretest, and post-tests and their scoring has been discussed above in Sec. VI C. The test performance was a reflection of individual skill. Two-way repeated measures analysis of variance (ANOVA) was performed and used to test for statistical significance, which was set to 0.05. Post-hoc pairwise comparisons were performed to examine specific information on differences among means. The data analysis was performed using SPSS [50]. The analysis of 40 students is reported.

Video data from multiple lab sessions were analyzed to identify episodes when students used advanced functionalities and exhibited effective handling of test and measuring instruments. In this study, we analyze one excerpt from an episode wherein students used advanced functions in a DSO.

Inductive thematic analysis was used to analyze the responses to the open-ended questions. The coding was done following the guidelines of Braun and Clarke [51]. One sentence was chosen as the unit of analysis. Two independent coders coded the student responses. After one round of coding, the two raters discussed and reached a consensus on the themes. Further discussion helped in refining and reviewing the emergent themes.

VII. RESULTS

A. Performance in tests

The mean score of the three tests for circuit analysis (Fig 7) shows progressive improvement in the ability of students to analyze circuits. The average performance for

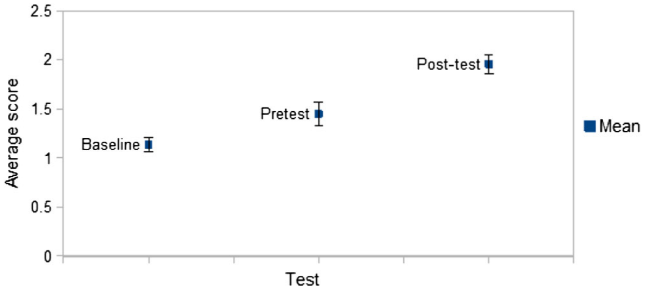


FIG. 7. Average class performance in circuit analysis.

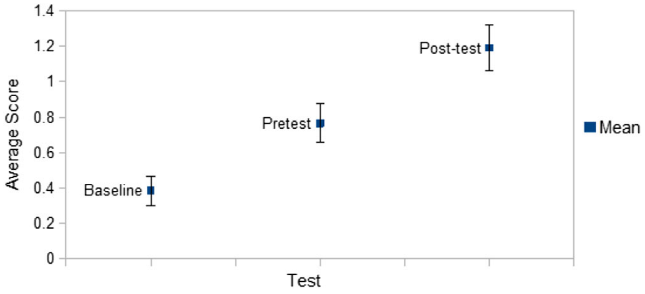


FIG. 8. Average class performance in circuit design.

criteria A2, A3, A4, and A6 of circuit analysis taken over all students yielded statistically significant main effects in the three tests [$F(2,78) = 43.835$, $p < 0.001$]. Multiple *post hoc* comparisons showed that mean difference between all the pairs, viz., pretest-baseline ($M = 0.528$, $SE = 0.106$), post-test-baseline ($M = 0.959$, $SE = 0.091$) and post-test-pretest ($M = 0.431$, $SE = 0.110$) were statistically significant.

Likewise, the mean score for circuit design (Fig. 8) shows progressive improvement over the three tests. The average performance for all criteria of circuit design construct considered overall students yielded significant effects in the tests [$F(1.627, 63.451) = 25.535$, $p < 0.001$]. Pairwise comparisons in the *post hoc* test showed that the mean differences between all the pairs, pretest-baseline ($M = 0.400$, $SE = 0.083$), post-test-baseline ($M = 0.770$, $SE = 0.106$), and post-test-pretest ($M = 0.370$, $SE = 0.129$), were statistically significant.

A detailed analysis of mean scores and differences for each criterion is shown in Table III. Considering circuit analysis skills, questions to test how the functionality of the circuit is affected by various components in the circuit (A1) were present only in the pretest and post-test. As a result, we performed a t test to determine the difference between the two means. No significant difference was seen in this criterion between pretest ($M = 1.9625$, $SD = 0.879$) and post-test ($M = 1.9375$, $SD = 0.8061$). A significant improvement was seen between post-test-baseline, and post-test-pretest for the criteria of identifying necessary and relevant mathematical relations between various dynamic quantities and parameters in the circuit (A2), applying relevant mathematical relation to determine various quantities at different locations in the circuit based on the mode of operation (A3) and in explaining behavior of the circuit by linking to theory and operational setup (A6). However, no significant improvement was observed in the criteria of analyzing how the performance of circuit changes when some components of the circuit are modified (A4).

Regarding circuit design skills, significant improvements were seen in the criteria of translating requirements to appropriate solution by applying relevant concepts (D1), devising a circuit topology that satisfies the specifications and representing it using a circuit diagram or block diagram (D4), and computing component values using relevant mathematical formula (D5). Performance in the criterion of suggesting and justifying chosen solution using theory (D2) showed no significant difference between pretest and

TABLE III. Results of repeated measures ANOVA and *post hoc* test for individual criteria in circuit analysis and circuit design performance (* indicates statistical significance).

Criterion	F ratio	p value	Mean difference pretest—baseline	Mean difference post-test—baseline	Mean difference post-test—pretest
Circuit analysis					
Identify governing equations (A2)	$F(2,78) = 71.906$	<0.001	−0.22	1.2*	1.42*
Apply mathematical relations at different circuit nodes (A3)	$F(1.644, 64.119) = 44.376$	<0.001	1.05*	1.58*	0.53*
Predict performance change due to modification of components (A4)	$F(1.628, 63.498) = 1.796$	0.18	0.27	0.08	−0.19
Link theory to observation setup (A6)	$F(2,78) = 28.109$	<0.001	−0.35	0.45*	0.81*
Circuit design					
Requirement translation (D1)	$F(1.591, 62.053) = 20.553$	<0.001	0.3*	0.95*	0.65*
Suggest and justify solution (D2)	$F(2,78) = 11.354$	<0.001	0.63*	0.3*	−0.33
Make valid assumptions (D3)	$F(1.623, 63.283) = 12.131$	<0.001	0.13	0.83*	0.7*
Derive circuit topology (D4)	$F(2,78) = 22.114$	<0.001	0.55*	0.99*	0.44*
Compute component values (D5)	$F(1.638, 63.864) = 18.718$	<0.001	0.3*	0.96*	0.66*

post-test means. Performance in making suitable and valid assumptions while selecting solution (D3) showed no significant difference between pretest-baseline means.

B. Usage of instruments

A video analysis of students' interaction during lab activities revealed multiple instances where they exhibited the ability to effectively use instruments in the lab. One such excerpt, where a student uses advanced DSO functions such as math function to derive voltage measures is presented below (TA-teaching assistant, S-student). The context is a push-pull amplifier and the student was investigating at what voltage the upper transistor was switching on and off. For this, the student connected one probe at signal input (base) and other probe at the emitter and used the subtract math function to view the output waveform on the DSO.

TA: What is the problem?

S: The math function should give subtraction of these two (signals) …Oh….it is correct. Math is (traces signal on DSO screen and muses to himself)…. almost half…1.4 by two is 0.7…

TA: So is it subtracting?

S: It is subtracting

TA: Why are you using math function?

S: I just want to see the voltage here (points to base-emitter region of upper transistor in push pull configuration). I just wanted to know if this part is greater or less than 0.7. This is my input (points to base) and this is—I connected here at emitter. So this (points to base) minus this (points to emitter) should give me the voltage. (manipulates the knobs on DSO, shifts trace to measure) 0.4….

TA: This transistor begins conducting at?

S: It should begin to conduct at 0.7 V or −0.7 V (manipulates knobs on DSO, brings measuring trace to negative part of signal, points to waveforms) this is fine—the negative half it should remain 0.7 V almost. In the positive….Oh in the positive half it should not conduct…it is correct!

TA: Ok what are you looking at?

S: One half cycle because the transistor is on only in half cycle.

We can see that in the process of tracing and reflecting on the output of the math function, the student verifies the working of one section of the circuit. The student is able to effectively use the DSO for verifying the circuit operation.

C. Student perceptions

Of the 45 students, 29 filled the perception questionnaire. The responses to the nine 5-point Likert scale questions (Fig. 9) show that most students strongly agreed or agreed, while fewer than 10% of students remained neutral toward five of the nine questions.

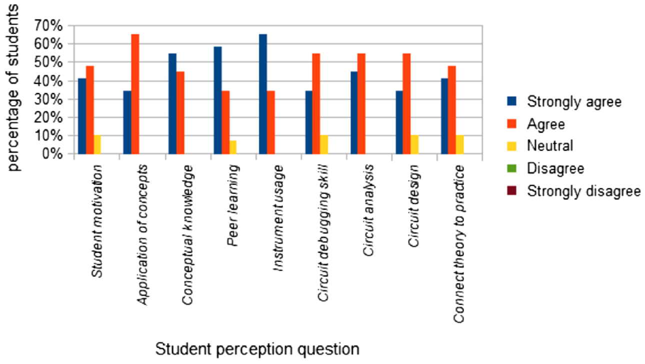


FIG. 9. Student perception of different lab activities.

With regard to the three open-ended questions, 27 students responded to the open-ended question on reasons for preferring the current lab format, 28 students responded to the question on describing how they benefited from the lab, and 25 students responded to reasons for not preferring the lab course. The responses ranged from one to five sentences and addressed multiple aspects of the lab. All responses were cogent. Thematic analysis of students' responses to the open-ended questions elicited the themes below. Frequencies of responses related to the corresponding theme are given in parentheses.

- Peer interactions (10 responses)—Peer interaction was perceived as an advantageous activity. One student mentioned the advantage of peer interaction as *"Mutual help and discussions lead to a way better understanding"*. Saving time, peer feedback, the opportunity to explore new ideas, and better understanding were the cited advantages with better understanding being the most popular perceived advantage of peer interaction.
- Affect (11 responses)—Students perceived lab activities to be enjoyable, interesting, exciting, and non-stressful while providing a comfortable lab setting. A few students mentioned an increased interest in electronics as seen in the quote, "I also developed some interest in electronics which had bored me in theory before." A few students found the open-ended tasks to be challenging: "The labs got a little frustrating at times when we had to think of circuit designs most of which were not very obvious."
- Conceptual understanding (10 responses)—Students found that the lab activities contributed toward increasing their conceptual understanding, especially about circuit components and electronic concepts. One student stated, "I got my concepts more clearer. Especially the lab in which we were made to understand that the ground of two DSO probes are shorted internally was my favorite, there couldn't have been a better way to teach that to us."
- Bridging theory and practice (17 responses)—Students felt that the lab activities provided them

with opportunities to bridge theory and practice. The students elaborated on this by mentioning that devising their own solutions, applying theoretical concepts, linking theory to observed behavior, and different considerations during the practical application of electronics helped them connect their theoretical knowledge to practice. One student wrote: “It made me think and devise solutions rather than cramming and following a given set of instructions mechanically.”

- Hands-on experience (22 responses)—A recurring theme was gaining hands-on experience via building circuits, developing debugging skills, practical exposure to circuits, and dealing with nonidealities. As one student stated, “It was nice to actually see and do things that we have been studying, there’s a huge difference between learning just the concepts and actually doing it practically yourself.”
- Comparison with conventional labs—An overwhelming majority of the students stated that they did not find any reason for not preferring this lab format. Four responses explicitly compared the current lab format to conventional lab courses they were taking concurrently. One student stated that “It is interactive and interesting and helps in more learning, even though it did require more work than the conventional ‘lab manual’ based labs.”
- Lab features (13 responses)—Students favored certain features of the lab such as a well-structured lab design, guidance by the instructor and TAs, nonprocedural tasks, no focus on memorization, emphasis on instrument usage, and keeping an experiment log with distilled understanding instead of simply a journal of experimental readings. As an illustrative example, one student said, “Unlike regular lab report writing that most labs require, these labs focused more on experimenting, thinking of ideas and applying them.”
- Problems with the lab structure (six responses)—A few students pointed to some of the problems they faced such as the shortage of TAs as a drawback. Some students felt that there should be a method to recap theoretical concepts.

The themes that emerged from the responses to the open-ended questions on preferring the ESSENCe lab and its benefits contained aspects such as peer interactions, bridging theory and practice, conceptual understanding, and hands-on experience of building and debugging circuits. As the ESSENCe lab pedagogy was not formally or explicitly discussed with the students, this analysis indicates that students recognized and acknowledged the importance of these aspects of the lab pedagogy.

VIII. DISCUSSION

To summarize the findings of the first research question “To what extent do students develop experimental problem solving skills in ESSENCe?,” a comparison of student performance across three tests at various points during the semester showed that average class performance in circuit analysis and circuit design skills steadily improved. Students came to this course with knowledge of basic analog electronic principles from a theory course in their first year. The baseline test established their ability to apply their theoretical knowledge in an experimental problem context. The progressive improvement in students’ experimental problem-solving skills in the pretest and the posttest indicates that the students have been able to apply their conceptual knowledge and lab experience to solve experimental problems. We believe that the ESSENCe pedagogical strategy enables students to connect the experimental problems, process and practices with theory using effective scaffolding strategies. The reiteration of this strategy over multiple contexts throughout the lab course helps students to assimilate experimental problem-solving skills and adopt it toward solving new problems.

While the overall improvement in both circuit analysis and circuit design was statistically significant, students’ performance was higher in analyzing circuits than in designing circuits. A possible reason for this could be that students in this study have previously been trained in analytical and problem-solving skills in different domains and contexts, including in the entrance test to the institute. However, they seldom encounter design activities before starting this course. This in turn points to the need for more design-related activities in lab assignments with additional scaffolding to equip students with design skills.

In circuit analysis, improvement was seen in identifying governing equations, applying mathematical relations at different circuit nodes, and in linking theory to operational setup. The in-semester lab exercises where ESSENCe pedagogy was applied over multiple sessions supported the students in acquiring disciplinary strategies and employing it in new contexts. However, no significant improvement was observed in the criterion of analyzing how the performance of a circuit changes when some components of the circuit are modified. This task requires students to use available information, known theory, interaction effects between different components of the system, and predict the consequence of a change—all of which makes the task complex and challenging. Also, there were fewer lab assignments involving this task, hence they had fewer opportunities to develop this skill. We surmise that this task requires additional scaffolding that focuses on helping students identify the key parameters that may be affected in the event of change.

Statistically significant improvement was observed in the circuit design criteria of requirement translation, derivation of circuit topology, and computation of component values. Rigorous exposure to concepts in different contexts coupled with multiple circuit design exercises during the lab course helped students consolidate their knowledge and apply them better at each subsequent test. However, justifying chosen solutions and making valid assumptions are cognitively more demanding and require students to reflect on a number of aspects of their solution. For novice students, critically evaluating different aspects of the solution can be daunting and they may not be sufficiently well equipped conceptually to cover the multitude of factors governing a new design. Students may therefore tend to desist from examining their idea in great detail and instead look for a surface-level match of the solution to the problem at hand. Also, students may make implicit assumptions that contribute to the difficulty in justifying chosen solutions. Written reports have been known to help in identifying and evaluating assumptions [46]. Additional scaffolding may therefore be required for both justifying chosen solution and making assumptions.

With regard to the effective usage of instruments, students quickly moved on from novice to comfortable level of usage. Being a first lab course in electronics, it was sufficient for students to use the general features of the instruments. In spite of this, we found instances where students made use of advanced features of DSOs. However, the use of research-grade instruments as a pedagogical strategy could be a potential limitation to generalizability of the ESSENCe pedagogical format. The cost of equipping a lab with sophisticated instruments can be expensive and may not be essential to a basic electronics lab. Given the nature of experiments in the first lab course in electronics, equipment with basic specifications may be sufficient, for example, an oscilloscope with a low bandwidth. Yet the availability of such instruments can motivate students to explore advanced features and optimize their solutions to experimental problems. This helps in expanding the repository of tools and techniques that students build up during their coursework, which can be valuable when they pursue independent research later. Additionally, the subsequent advanced electronics labs in the program contain experiments that warrant the usage of sophisticated instruments.

Our second research question addressed student perceptions about the lab, which were predominantly positive. This was reflected in their responses to the open-ended questions. Students welcomed the hands-on nature of the lab, the opportunities to collaborate and explore the concepts, and the strong emphasis on learning. They also appreciated the move away from routine procedures. Our findings align with previous studies which discuss the positive attitude of students in inquiry-based laboratory curricula in terms of course subjects and better content comprehension [52]. However, students pointed to a few challenges with the ESSENCe pedagogical format. The shortage of teaching assistants was a recurring problem. Due to the cognitively demanding lab, TA feedback was continually sought by students. A second issue was related to the effort required. Each ESSENCe lab relies on a prelab assignment and readings to prepare students for the in-lab activities. This entails effort by students beyond the lab time slot. When students did not complete the prelab activities, they came to the lab ill-prepared for the session and found the in-lab assignment daunting. Though peer interaction, embedded information source, and careful structuring of lab assignments mitigate the problem, students are left with lesser time to explore multiple experimental strands during the lab session, thereby missing out on valuable learning. Overall, while nearly two-thirds of students (29/45) responded to the open-ended questions, it is possible that the students who did not respond may have faced difficulties that did not come to light. Further studies could include deeper analyses such as observations while students perform the lab as well as detailed student interviews, with an attempt to include a wider range of students.

Though considerable thought was expended during the research design, this study has limitations. First, the structure of the curriculum with a fixed number of students per lab ruled out an experimental study design at this time. Consequently, the attribution of ESSENCe pedagogy toward the development of students' experimental problem-solving skills cannot be causally established. Second, the skewed gender ratio inhibits any further analysis related to gender. In prior research, the role of gender in group composition and participation has been studied [53], as well as the effect of interactive engagement techniques on women students [54]. We acknowledge the limitation in this study in understanding the experiences of women students. Third, the implementation of the ESSENCe pedagogical approach requires significant human resources and effort in terms of knowledgeable TAs and considerable time spent by the instructor to design, test, and modify the assignments if needed.

Our study confirms established results that nontraditional, problem-solving labs contribute to conceptual understanding, mastery of equipment, qualitative evaluation of circuits, and development of scientific abilities [12,17,27]. In addition, our study establishes that careful design of pedagogy for lab can nurture students' experimental problem-solving skills and bring about a positive outlook toward the subject as a whole. Since this study, the ESSENCe lab has been implemented for five more years. The resources we have developed are publicly available on the Electronics Laboratory Resource Website, Department of Physics, Indian Institute of Technology, Bombay [55]. We hope other instructors will be able to use and build upon them in their teaching labs.

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