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Evidence-based Teaching Practices in Physics: An Overview on Authentic Teaching and Learning

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Abstract. Learning is inherently a social process as outlined by the theory of constructivism. Learners construct knowledge via active participation and experience. Meaningful learning requires multiple means of engagement, representation of materials, and assessment. The current challenges in physics teaching-learning are understanding of the learning mechanism, designing of proper instructional materials, and use of student-engagement strategies that help them in long-term retention of the concepts. Pedagogical research shows that the teaching-learning process should be learner-centered where the learners will take ownership of their learning. This paper provides a review of various Research-Based Instructional Strategies (RBIS) designed to enhance physics education through learner-centered and authentic teaching practices. The literature shows that the use of RBIS fosters a more engaging learning environment, students' deeper understanding of the material, and higher retention rates. This paper also explores the limitations of traditional lecture-based pedagogy and emphasizes the need for active learning approaches. Furthermore, it addresses challenges in implementing RBIS, such as large class sizes, time constraints, instructional resource availability, and so on. Finally, we summarize our effort to disseminate the RBIS within the Nepali physicists' community.

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INTRODUCTION

When you ask students about physics, their responses, in general, are 'Physics is difficult' [1], 'It's memorizing or working through difficult equations without real applications outside the classroom' [2], or 'Physics would be difficult, irrelevant and boring' [3] or something like this. In general, students with Science, Technology, Engineering, and Mathematics (STEM) majors in a US college or university are required to take a few physics courses for their degrees. Students who take physics as a part of their academic requirements may retain the physics knowledge only a little or nothing. Many students who cannot perform well in introductory physics courses end up with horrible experiences leading to the sentiment of 'I hate physics' or 'Physics is not my subject'. We wish we could transform this sentiment to 'I enjoyed learning and doing physics', 'I enjoyed this physics class', 'I recommend my friend to take this physics class', etc.

In this context, a very relevant question to ask is: 'What can be the source of the problem?' In every field, some work-related training is required before someone is allowed to perform their job. Usually, if someone has an academic degree and has done a good research in their areas of research, colleges and universities hire the person as a faculty, provide an office space and some basic equipment, and they are assumed to be ready for teaching. It is an unstated assumption that if someone has a degree in physics, they must know how to teach [4]. However, instructors may not have sufficient knowledge of effective teaching and learning, and might rely on the predominant mode of teaching by lecturing. Instructors might have a flawed understanding on how we learn, and they tend to suggest to the struggling students some ineffective methods of learning like 'study hard' [5].

LEARNING MECHANISM

Learning, especially in an academic setting, is a complex process. It involves several factors including cognitive

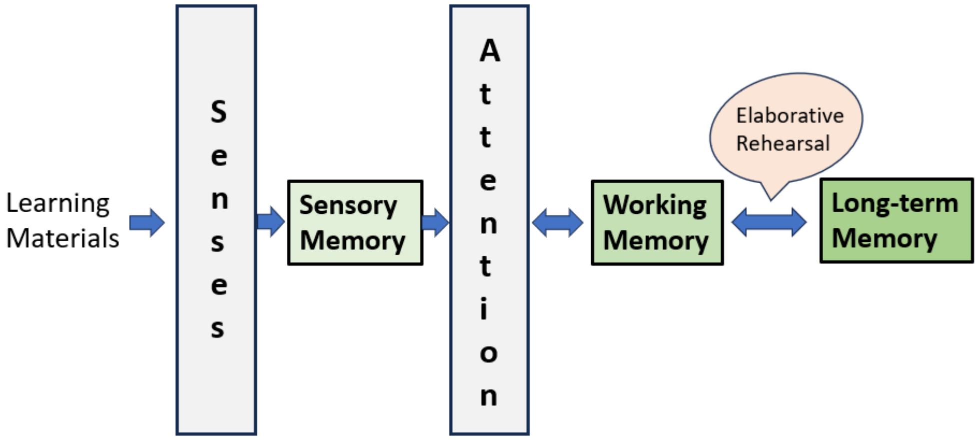

FIGURE 1. Human learning mechanism, adapted from the Ref. [5]

processes such as attention, working memory, and executive function. Executive function involves students' prior knowledge, the concept to be learned and how it has been presented, and learning strategies employed by students [5]. Learners construct knowledge through experience or doing things by being *active physically and mentally* in the learning environment rather than just by being *passive listeners* [6].

According to the widely used models of learning, the new information is first perceived by the senses and passed to the sensory memory [Fig. 1]. Based on the attention, this information will pass to the working memory (WM) or it will be lost immediately in a fraction of a second. Information in working memory stays for a few seconds. It can be passed to the long-term memory (LTM) through elaborative rehearsal. Learning is the encoding of information in the LTM [7]. The body of information in LTM is called schema. It is distributed in clusters of neurons in the brain. Storing information in the LTM is more effective if the information makes sense to the learner and is related to the learner's interests and prior knowledge. For new information stored in the LTM, the connection between clusters of neutrons is weak, which can be strengthened by rehearsal, a necessary process for deeper learning [4]. Two separate channels - *auditory* and *visual* for information flow to the brain are responsible for coding sensory inputs in the WM. The information presented visually and verbally is more likely to pass in the LTM [8–10].

Authentic learning implies storing information in the LTM, effortlessly retrieving it, and applying the sets of information in various contexts. So, attention and elaborative rehearsal are the two primary aspects of authentic learning. This will happen only when students are effectively engaged in learning through various learner-centered pedagogical activities. Still, in many institutions and disciplines, lecturing is a predominant mode of instruction. But, research shows that students lose their attentiveness quite quickly: after ten minutes of lecture, their attentiveness toward the lecture starts plummeting, and it will decrease significantly toward 0% in about 30 minutes or so [4]. Therefore, we should not be surprised if students do not learn the materials that we cover after about 20 minutes or so into the lecture.

Furthermore, there are a few choke points and pitfalls in effective learning [5]. The choke points include limited mental effort or concentration. New and complex materials have a higher cognitive load which requires more concentration to learn [11]. In addition, our working memory is limited, and cannot process more than four chunks at a time, where a chunk refers to organized and coherent information acting as a single unit in WM [5, 12, 13]. Therefore, improperly designed instructional materials create an unnecessarily higher cognitive load, causing negative effects on learning.

The pitfalls of learning include [5]:

(i) multi-tasking,
(ii) less effective study methods,
(iii) overconfidence, and
(iv) dissipation of information over time.

The human brain is designed to do one thing at a time. Students who think they are good at multi-tasking, in reality, they are not. They may suffer from a plethora of digital distractions in the learning environment [14]. Students generally use ineffective learning methods like *mass practice*, and *mindless reading and highlighting*, which are easy to do but negatively affect the deep-learning. Some students may be overconfident, and assume that they can digest the learning materials in a short period of time. This attitude limits them from putting enough effort into learning [5]. The overlap of learning materials in the LTM also causes limitations in learning. Furthermore, the information in our LTM does not stay forever; it decays over time and needs rehearsal [4].

The next important stage of learning is the retrieval of information from the LTM. This process can be fast, effortless, and automatic through iterative rehearsal [5].

TEACHING PEDAGOGY AND ITS EVOLUTION

The dictionary definition of pedagogy is the art, science, or profession of teaching [15]. Pedagogy spans a wider range of issues and topics than just its dictionary definition [16]. Majority of the academic institutions still follow the traditional teacher-centered pedagogy in their instructional activities, where the teacher is like a 'sage on the stage' [17]. This means that a teacher is the source of knowledge who 'pours' the knowledge on the 'empty' brain of the disciples.

Although a good traditional lecture serves several useful purposes, they are not helping much for learning. Research-based instructional strategies (RBIS) advocate for the learner-centered pedagogy for an effective teaching-learning process. Unlike lecturing as done in teacher-centered instruction, a teacher should play a role of a 'guide on the side' [17], and facilitate the student-learning by involving the students in various activities where they perform the activities and learn. When they learn this way, they will feel proud of their learning, i.e., they will take ownership of their learning [19–22].

For teachers to be an effective guide, they should have a strong pedagogical content knowledge (PCK) which is the blending of pedagogical knowledge (PK) and the content knowledge (CK) [18]. This means that they should be well-trained on the the content knowledge, i.e., they should have knowledge on 'what to teach' as well as on the pedagogical knowledge i.e., they should have knowledge on 'how to teach' the given content in an artistic way so that the learners are motivated in learning. We can represent the PCK space for an effective instruction as the intersection of the two circles in a Venn diagram [Fig. 2], where the two circles represent the pedagogical knowledge (PK) and the content knowledge (CK).

With the advent of educational technology, teachers in modern-day classrooms should also be familiar with relevant technologies and feel comfortable using them to create an effective learning environment. This means that an effective teaching-learning happens in a classroom with an instructor who has technological, pedagogical, and content knowledge (TPACK) [23]. We can represent the TPACK space for an effective instruction as the intersection of three circles in a Venn diagram [Fig. 3], where the three circles represent the technological knowledge (TK), the pedagogical knowledge (PK), and the content knowledge (CK). The large dashed circle highlights the organizational and situational constraints that teachers work within [24]. Instructional technology encompasses a broad range of tools including learning management systems (LMS), presentation hardware and software, personal response systems, simulations, interactive multimedia, communication tools, and generative AI like ChatGPT [4, 25]. In addition to the knowledge on content, pedagogy and educational technology, the instructor should be familiar with designing a curriculum and setting up learning outcomes in a proper level as guided by the Bloom's taxonomy [26].

Several efforts have been made to enhance effective teaching and learning in the past and are still ongoing. More than four dozens research-based instructional resources have been developed so far. They mainly focus on course design, classroom engagement, multiple means of representation, and assessment [27]. The following list gives some research-based instructional strategies or tools in various disciplines:

- One-minute Paper [28]
- Think Pair Share [29]
- Lecture Pause [30]
- Active Learning Problem Sheets [31]
- Wait Time [32]
- Peer Instruction [33]
- Interactive Lecture Demonstrations [34, 35]
- Activity-Based Physics Tutorials [33]
- Muddiest Point/Exit Ticket [36]
- Context-Rich Problems [37]
- Experiment Problems [38]
- Cooperative Group Problem Solving [39]
- Just-In-Time Teaching [40]
- Modeling Physics [41]
- Open Source Tutorials [42]
- Open Source Physics [43]
- Overview, Case Study Physics [31] [44]
- Physlets [43]
- Ranking Tasks [45]
- Real-Time Physics/Tools for Scientific Thinking Labs [46]
- Socratic Dialog Inducing Labs [44]
- SCALE-UP, Studio Physics [47, 48]
- Task Inspired by Physics Education Research (TIPERs) [49]
- Workbook for Introductory Physics [50]
- Tutorials in Introductory Physics [51]
- PhET Simulations [52]
- HTML5 Simulations for Introductory Physics [53]

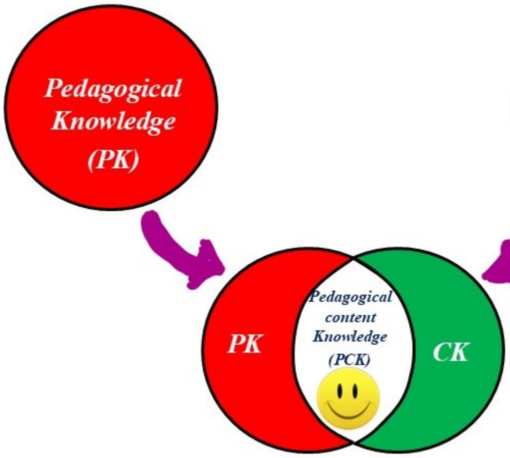

FIGURE 2. The intersection of the two circles represents the space for the pedagogical content knowledge (PCK), Ref [18].

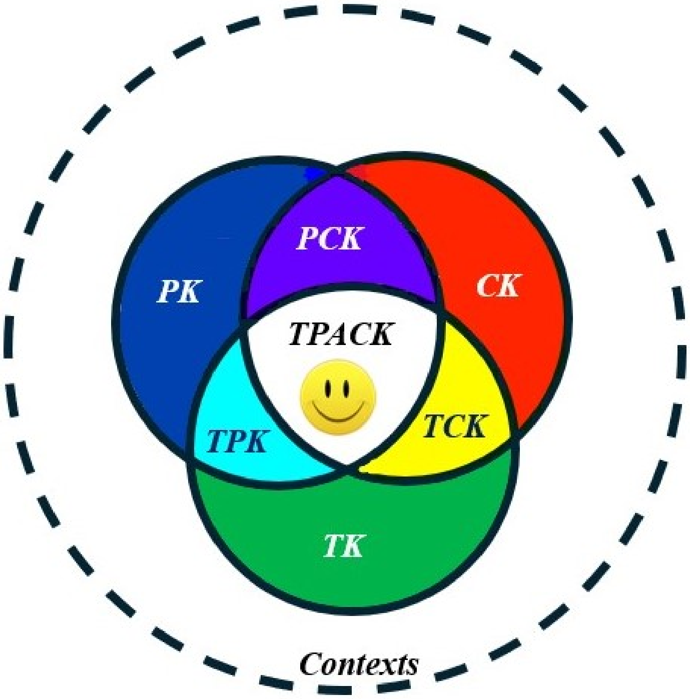

FIGURE 3. The intersection of the three circles represents the space for the technological, pedagogical and content knowledge (TPACK). The figure was adopted from the Ref. [23].

- Structured Quantitative Inquiry Labs (SQILabs) [54]
- Investigative Science Learning Environment (ISLE) [55]
- Undergraduate Research Experiences (UREs) [56]
- Inquiry-Based Learning (IBL) [57]
- Scientific Reasoning Labs (SRL) [58, 59]
- Video-Based Labs [60]
- Inquiry-Based Experimental Physics [61]
- Game and Game Theory [62]
- Problem-Based learning [63]
- Flipped Classroom [8]
- Snowball [64]
- Class Discussion [65]

- Gallery Walk [66]
- Matches [67, 68]
- Thought Barometer [69]
- Peer-Evaluation [70]
- Re-Thinking [71]
- Drawing/Concept Mapping [72]
- Narrative Story Telling [73]
- Modeling [74]
- Jigsaw Method [75]
- Place-Based Learning [76]
- Think Aloud Teaching Strategies [77]
- Think Aloud Pair Problem Solving (TAPPS) [78]
- Chunked Problem Analysis [79, 80]
- Working through Work-Out Problems [81]
- Self-Evaluation [82]
- Physics Lecture Demonstrations [83],
- Conceptual-Inquiry Based Labs [84, 85], and so on.

Studies show that student learning significantly improved when the instructor moved from traditional transmission style teaching to student-centered, interactive instructions using RBIS. Students' average examination scores are observed to increase by 6% in active-learning classes compared to traditional lecture-based classes. The failure rates in traditional classes were found to be 1.5 times higher than that of the active-learning classes [86]. This finding compels to reevaluate the definition of teaching from 'To show or explain something' to 'To cause to know something'. The teacher should not function as the sole source of wisdom and knowledge, but should be more as a coach or guide, whose task is to help students acquire the desired knowledge and skills for themselves, as opposed to being 'sage on the stage' [4].

Some of the commonly used RBIS from the list above which can be implemented in any type of classroom settings without introducing further financial or space constraints are briefly described in the following:

One-Minute Paper: The instructor asks students in the class to write a paragraph describing what they learned in the lab or lecture. This encourages students to think about what they learned, a meta-cognitive process for deeper learning.

Wait Time: Asking open-ended questions frequently during class discussions enhances students' learning. After the instructor presents a question in the class, instead of jumping into it and answering the question, allowing some wait time until the students begin to discuss, promotes the students' deeper learning [87].

Think-Pair-Share: The instructor presents a question to the class and asks students to think and write down their responses individually. Then the students will form a group, share their answers, refine, and synthesize them. The group comes up with an answer they agree. Then one person from the group presents their response to the class. Sometimes, if the group cannot agree on a single answer, they rank the possible answers based on the number of votes each one receives.

Polling: The instructor presents a question and asks students to answer it using some form of polling like *Poll Everywhere*, *Clicker*, or *Index card* which helps the instructor evaluate student learning instantly. This also gives an opportunity to the instructor to revise and update the instructional material or strategies accordingly.

Lecture Pause: During the class session, when the instructor moves from one concept to another, a short pause allows students to digest or internalize the material just covered.

Muddiest Point or Exit Ticket: At the end of a class or lab session, it is good to ask students to write down what was not clear to them in the class. This will help the instructor address any confusion in the following class.

Peer Instruction: The instructor presents a question to the class, generally in a multiple-choice format. Students think about and answer the question individually using a polling system. Then they discuss their answers with their peers in a small group, revise their reasoning, and answer the same question again.

As discussed above, deep learning of the material requires activating our brain, and this can be made possible through active engagement in learning. 'Active learning (AL) instructional activities involve students doing things and thinking about what they are doing' [88]. Students' attention increases dramatically by introducing relevant activities or some RBIS in the classrooms. The attentiveness of the learners was observed even much higher compared to the highest possible level of attentiveness in a traditional lecture [4]. Attention is directly related to passing information to WM and LTM, and learning. AL with RBIS influence student engagement in learning, promote better performance on the course, and improve long-term retention of skill sets.

WHY DO WE NEED RBIS?

RBIS are student-centered teaching strategies or tools that focus on scaffolding the student learning on what they do in class. The uses of RBIS have several advantages which creates a framework for students to work in a group. When individuals get stuck, groups complement and share resources, students see and learn material from their peers, and they are more willing to ask questions. Low-performing students can learn from their high-performing peers in a group, and high-performing students learn better when they teach [89]. Also, the group work produces the following [90]:

(i) student-student interaction and student-faculty interaction,
(ii) higher-level thinking skills,
(iii) better attitudes towards the material and more motivation,
(iv) better interpersonal skills,
(v) understanding of the professional environment,
(vi) lower anxiety (less competition),
(vii) higher class attendance, and
(viii) fun for everyone.

Research shows that student and faculty interactions using RBIS produced higher achievement gains. For example, implementing one of the RBIS, *Peer Instruction* techniques in the classroom has been shown to triple student-learning gains while also enhancing their conceptual understanding and problem-solving skills [91].

COURSE DESIGN AND ASSESSMENT

The first step in teaching a course is to develop a syllabus with clearly stated student-learning outcomes. Learning outcomes are the explicit statements that students should be able to do after completing a course [4]. They should be written in measurable terms like ‘explain’, ‘present’, ‘create’, ‘evaluate’, ‘design’, etc., but the verbs like ‘know’, ‘learn’, ‘understand’, ‘appreciate’, etc., being not easily measurable, should be avoided [4].

The instructors should make assessment plans to measure the learning outcomes through the design and implementation of suitable learning activities. This commonly adopted model of course design is known as the backward design model [92].

Since students use learning outcomes as a study guide, clarity in writing them is essential. The learning outcomes can range from knowledge and understanding levels to the application of the principles to high-level problem-solving, designing, and creating something tangible. The revised Bloom’s Taxonomy [26], based on the Original Taxonomy by Bloom et al. [93] outlines six levels of learning outcomes: remembering, understanding, applying, analyzing, evaluating, and creating [Fig. 4].

Knowledge or remembering is the first stage of learning and lies at the bottom of the learning pyramid. We can only move up in the pyramid one step at a time. Action verbs outlined in Bloom’s taxonomy [93] will help to set both low- and high-level student learning outcomes. A course design should emphasize high-level learning outcomes, and valuable class time should not be spent solely on low-level recall or basic reasoning. Bloom’s taxonomy can help the instructor map students’ learning during the semester and design their course material to achieve their instructional goals.

We will briefly explain the various levels of learning outcomes in the context of learning Newton’s laws of motion.

(i) Remembering: The learning outcomes in this category are in the lowest level of the Bloom’s taxonomy pyramid. It is simply the retrieving of the relevant knowledge from long-term memory including recognizing, recalling, etc. For example, after learning the topic of Newton’s laws of motion, the learner will be able to recall the relation between net force acting on an object with its mass and the acceleration.

(ii) Understanding: This is the second level of the learning outcomes in Bloom’s taxonomy which refers to determining the meaning of instructional messages, including oral, written, and graphic communication. After mastering this level of the learning outcomes in a topic, the learner will be able to interpret, exemplify, compare and contrast on various concepts involved within that topic. For example, after mastery of this level, a learner is expected to explain the meaning of the Newton’s laws of motion.

(iii) Applying: In this level, a learner will be able to carry out a procedure in a given situation. For example, after learning Newton’s laws of motion, the learner will be able to solve numerical problems by applying Newton’s second law equation.

(iv) Analyzing: This level of the learning outcomes include the breaking of material of topic into its constituent parts and detecting how the parts relate to one another and to an overall structure. For example, a learner will be able to see all the forces included in the net force in Newton’s second law equation and analyze why only the net force comes into play to produce acceleration on the object under action of multiple forces.

(v) Evaluating: This level of learning outcomes refers to the making of judgements based on the criteria and standards. In the context of our example of Newton’s laws of motion, for a given problem, a learner will be able to dissect a complex problem and pick the correct Newton’s law of motion to solve it completely.

(vi) Creating: This is the highest level of learning outcomes in the Bloom’s taxonomy pyramid. In this category, a learner will be able to put elements together to create something tangible or make an original product. For example, the learner will be able to generate a report on a project based on Newton’s laws of motion or even can create a workable device which is based on Newton’s laws of motion.

Teaching a course for the first time requires very careful planning. As outlined by Felder and Brent [4], new instructors should avoid the following mistakes:

(i) developing everything from scratch,
(ii) trying to cover everything in class, and
(iii) trying for perfection.

It is always beneficial to reach out to colleagues who have taught the course before so that the new instructors don’t have to reinvent the wheel. The instructional materials

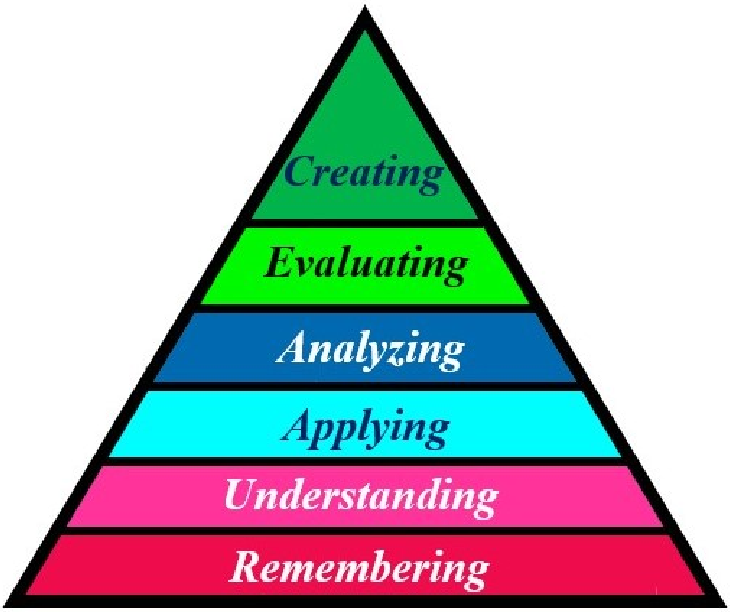

FIGURE 4. A pyramid showing Bloom's Taxonomy based on the Ref. [26].

should motivate students to explore the content independently rather than attempting to cover everything in them. The effort to look for perfection might take a lot of time to make the instructional material so-called 'perfect'. As a result of this, new instructors lose a large chunk of time without significantly enhancing student learning. The common practice is, for an hour-long class, the preparation time should not be longer than two to three hours [4]. Implementing RBIS in the classroom might take longer time in comparison to standard traditional lecture set-up. Instructors may not be able to cover everything initially planned. This issue can be addressed by providing handouts to the students.

Low-stake assignments like quizzes with multiple attempts and minimal point deduction for each attempt help students learn from their mistakes. The diverse and inclusive forms of assessment techniques should be used. If the majority of students perform poorly on an assessment, it is a good indication that something is not going well in the course. One strong possibility is that the assessment tools and learning activities may not have been aligned with the learning outcomes. Sometimes instructors have practices in curving the grades to pass more students in the course. However, research suggests that curving students' grades is not the right way to demonstrate the achievement of the learning outcomes. Instead, the instructors are recommended to consider modifying the course accordingly.

Besides that, the instructors should monitor students' learning continuously throughout the course. This can be done using personal response systems such as think-pair-share, poll everywhere, index cards, asking questions, one-minute paper, and so on. Furthermore, mid-course and end-of-course surveys can be helpful to improve the quality of the instruction and student learning.

EFFECTIVENESS OF PHYSICS LAB COURSES

Instructional laboratory courses are integral parts of undergraduate physics education and are expected to play a crucial role in enhancing students' learning through hands-on experimentation and real-life applications. Either they are stand-alone labs (held in different locations and times from lecture courses, receiving separate lab grades or grades that are composite of two parts of the course) or completely integrated into lecture classes like in-studio setup. Most universities and colleges still use traditional lab courses which are more structured like a cookbook as they have everything in the lab book including what equipment to use, how to set up the equipment, which button to push, what data to collect, and what to analyze [94]. Traditional labs are primarily designed to reinforce the content knowledge from the lecture class. However, the study shows that students who attend traditional lab and lecture courses and just lecture courses have no significant difference in their conceptual understanding [95, 96].

In traditional labs, student follows the step-by-step procedure in the lab using complex high-precision equipment, fill out the worksheet, and earn good grades but after they leave the lab room or the next semester, they don't know what they did. This type of lab does not engage students in the decision-making and critical thinking behaviors of the experimentalists [94].

As recommended by the American Association of Physics Teachers (AAPT) lab guidelines, laboratory goals should include [97]:

(i) Constructing Knowledge,
(ii) Modeling,
(iii) Designing Experiments,
(iv) Developing Technical and Practical Skills,
(v) Analyzing and Visualizing Data, and
(vi) Communicating Physics.

Based on the AAPT guidelines and learning goals, there are several lab courses developed so far including Conceptual Inquiry-Based Labs [84, 85], Scientific Inquiry Labs [58, 59], ISLE [55], SQILabs [54], and so on, to foster the 21st-century skill sets and competencies for students.

Challenges in Implementing RBIS

There are a few challenges to implementing RBIS in the classrooms. Those challenges include - large class sizes, more rewards in research over teaching, fear of failure and the chance of losing the job, lack of time in designing and preparing the instructional materials, and age of the instructors. Research carried out by Henderson et al. shows that 88% of the faculty are aware of the RBIS, 72% of them tried at least one RBIS in their classes, one-third of them do not continue using it, and 48% of the faculty are using one or more RBIS in their classroom [27].

Unfortunately, one-third of the faculty would not continue using RBIS in their classroom after they tried it. This indicates that more support is needed for faculty for the implementation and continuation of using RBIS in their instructions. Furthermore, their research shows that factors such as faculty age, institution type, percentage of job-related teaching (full-time, part-time, temporary, or permanent), the need for high research productivity, and large classes were not found to be barriers to using at least one or more RBIS in the classroom [27].

RBIS Dissemination in the Community

We can implement one or more RBIS in any classroom environment. It can be *Think-Pair-Share*, *Lecture Pause*, *One-minute Paper*, *Exit Ticket*, *Self-assessment*, *Chunked-problem Sets*, *Think-aloud Problem Solving*, and so on. The use of RBIS by instructors is observed directly correlated with their teaching-related journal reading habits and attending workshops [27].

We have been doing some activities to disseminate the RBIS for the last few years in collaboration with the Association of Nepali Physicists in America (ANPA) to make the Nepali physicists community aware of the RBIS. We started monthly virtual meetings on *Innovative Teaching and Scholarship of Teaching and Learning* in July 2022. There were multiple presentations in these meetings from the experts within and outside the ANPA community. To make this process more formal, ANPA established the Physics Education Research (PER) Division in February 2024. So far, we have more than thirty presentations on topics related to RBIS including curriculum design, inquiry-based laboratory development instructions, active learning strategies like studio style and SCALE-UP teaching environments, pedagogical-content knowledge, application of instructional technology including large language models like ChatGPT in physics instruction, and so on. These meetings were regularly attended by physics faculty members, postdoctoral researchers, and graduate and undergraduate students from the ANPA community and beyond around the world.

CONCLUSION AND DISCUSSION

In this paper, we briefly discussed student learning mechanisms, some currently exercised pedagogical strategies, curriculum and course designing models, physics laboratory instructional techniques, and assessment strategies. We reviewed various forms of RBIS for authentic teaching and learning. An adoption of at least one of these RBIS at a time in our classrooms will be a good start toward the learner-centered pedagogy. This will enhance students to focus on the material, increase class engagement, and provide better scaffolding for authentic learning experiences. Educating instructors about RBIS, learning mechanisms, classroom engagement techniques, and equitable assessment methods can significantly improve teaching and learning across all disciplines. This can be done in schools, colleges, and universities or in a community before the academic sessions start and by continuing various forms of training seminars and workshops throughout the academic year.

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