Exploring Student Engagement and Teacher-Student Interaction Patterns in Collaborative STEM PBL courses through Epistemic Network Analysis

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Abstract: To assess junior high school students' engagement in collaborative STEM project-based learning courses, this study employed a web-based observation protocol called COPIE-STEM to collect classroom observation data. This protocol coded data based on the ICAP theory and teacher instructional approaches. Over the course of six weeks, data on student engagement behaviors and teacher behaviors were gathered. In addition to using coding and counting methods, Epistemic Network Analysis (ENA) was employed to explore the trajectory of the STEM-PBL course during these six weeks. The results revealed that passive student engagement behaviors and teacher-centered behaviors clustered on the left side, while active student engagement behaviors and student-centered teacher behaviors clustered on the right side. Furthermore, examining the network graphs for each week's courses showed that as the course progressed, instruction shifted from teacher-centered to student-centered, and students exhibited higher levels of engagement. These findings provided insights into the dynamics of STEM-PBL classrooms.

keywords: STEM project-based learning, student engagement,instructional approach, Epistemic Network Analysis

1. Introduction

STEM project-based learning (STEM-PBL) is an educational approach that involves engaging students in real-world problems and encouraging them to investigate and solve these problems through multidisciplinary knowledge integration. By working collaboratively in groups, students can develop their problem-solving and critical-thinking skills while producing solutions or works (El Sayary et al., 2015). The effectiveness of STEM-PBL has been proven, and using this model for teaching can enhance learning outcomes (Saraç, 2018). In order to better understand the behavior of teachers and students, many classroom observation protocols have been developed for STEM-PBL courses (e.g., Smith et al., 2013; Hsiao et al., 2022). An important next step is analyzing data and depict a realistic picture that reflects what is happening in the classroom, assisting teachers and students to adapt in the PBL environment.

In the past, most of the data collected in classroom observation were coded and counted for descriptive analysis that unfortunately omits critical insights into how variables interacted and evolved (Csanadi et al., 2018; Rojas-Drummond et al., 2013). The dynamic aspect of how teachers conduct their teaching and how students engage in learning was not explored much. Therefore, this case study adopted the epistemic network analysis (ENA; Shaffer et al. 2009; Shaffer, 2017), which is an analytical method modeling behaviors in temporal framework, to understand STEM-PBL, particularly the interplay between instructional approaches and learning engagements.

2. Literature Review

2.1 Student Engagement and Instructional Approach

Student engagement includes behavioral, cognitive, and emotional involvement (Fredricks et al., 2004). Among various theories of student engagement, we find the ICAP theory (Chi, 2009; Chi & Wylie, 2014) to be the most suitable for characterizing student participation in classrooms. The ICAP theory pertains to students' cognitive engagement in learning activities, encompassing Interactive, Constructive, Active, and Passive modes, with a hierarchy of I > C > A > P. Chi et al. (2018) used this theory to design professional development programs for teachers, demonstrating that ICAP is relevant not only to students but also as a guide for teacher behaviors.

Based on the instructional design, the interactions between teachers and students can manifest as either teacher-centered or student-centered. Distinct student responses seem to emerge aligned with each instructional approach. In teacher-centered classrooms, the teacher serves as the transmitter of knowledge, while students are primarily passive listeners. In contrast, student-centered classrooms foster more active student engagement, with teachers playing a role in assisting students' learning (Serin, 2018). To sum up, this taxonomy of instructional approach and the ICAP framework form the foundation for categorizing student behaviors and teacher behaviors in this study.

2.2 Epistemic Network Analysis in Education

In previous related research, coding and counting were commonly used, with coding frequency as the basis of analysis. This approach treats behavior captured in a time interval as independent entities, thereby overlooking the connections between them (Swiecki et al., 2020). As a result, the sequential relationships between interactions among participants cannot be discerned. In contrast, Epistemic Network Analysis (ENA) combines qualitative and quantitative analyses, enabling to examine complex processes of human interaction. ENA's theoretical foundation originally lies in the epistemic frame theory (Shaffer, 2017), which views learning as the transformation of an individual's epistemic network manifested in discourse. This network evolves over time during and after the learning process.

Lately, the technique of ENA has been applied in different research domains. The most relevant to our study is the research of collaboration in classroom. For instance, Nachtigall & Sung (2019) conducted a study in an environment characterized by productive failure. In this study, students attempted to solve problems on their own before receiving delayed instruction. Subsequently, ENA was employed to compare the differences in problem-solving approaches between high quality (HQ) solution groups and low quality (LQ) solution groups. The HQ group engaged in debates concerning the problems, while the LQ group focused more on the instructions provided on the worksheet. Peng, Wu, & Hu (2020) conducted an Epistemic Network Analysis (ENA) on the discussion process of pre-service STEM teachers regarding how to design STEM lesson plans in an online context. Their analysis indicated that, despite tutor providing assistance to the low-performing group, the objectives within the lesson plans designed by this group were inconsistent. On the other hand, the high-performing group systematically designed their lesson plans based on the objectives, following a step-by-step approach to intricately incorporate the content relevant to what students were expected to learn. These examples have showcased how this innovative analysis method offers a distinct perspective on the data, surpassing the traditional approach by providing valuable insights.

In most studies, information is collected through methods such as audio recordings, video recordings, or recording interactions via online learning platforms (Elmoazen et al., 2022), followed by additional coding. However, in our research, we employ a classroom observation protocol to collect data in a physical environment. We observe the teaching and learning processes in STEM-PBL courses over the span of six weeks, with each week focusing on a different theme. Using ENA, we seek to comprehend the overall behaviors of teachers and students across this series of sessions, as well as the variations in behaviors between teachers and students from week to week. Therefore, the following research questions are posed:

RQ1: What is the distribution of individual behavior code frequencies for teachers and students in each week?
RQ2: What does ENA portray in the overall contextual relationship between teacher and student behaviors throughout the six-week course?
RQ3: Does the ENA method identify subtle differences in teacher and student behaviors across the six-week course?

3. Methods

3.1 Study Context and the Participants

This is a case study focusing on a school in southern Taiwan that adopts a STEM-PBL curriculum emphasizing on Sustainable Development Goals (SDGs) related challenges. Because the hot and humid summers and mosquito issues in the region, the project-based curriculum aims to equip 8th-grade students with relevant knowledge to develop a mosquito prevention product. According to the course plan, the development of the anti-mosquito sprayer was carried out step by step. The observation period lasted for six weeks, with each class lasting 45 minutes. There was a total of 30 students in the class, divided into groups of 6 students each.

3.2 Data Collection

3.2.1 COPIE-STEM Protocol and Coding Framework

To collect behavioral data, we adopted COPIE-STEM, an observational protocol developed by Hsiao et al. (2022) which is operated on a web-based platform called the "Generalized Observation and Reflection Platform" (GORP; University of California-Davis, n.d.). The protocol was divided into two parts: student behaviors and teacher behaviors. The coding framework for the student behaviors (Table 1) is based on the ICAP theory (Chi, 2009; Chi & Wylie, 2014), while the coding framework for teacher behaviors (Table 2) classified into three categories: teacher-centered, student-centered, or transitional. The raw data, as presented in Figure 1, are collected at 1-minute intervals. A "1" indicates the occurrence of a specific coded behavior, while "0" signifies the absence of that behavior. Finally, a total of 857 student and teacher behavior data were collected in this study, which will be used for subsequent analysis.

Table 1. *A Coding Framework for Student Engagement Behavior in the Classroom*

Code	**Definition**	**EXAMPLE**
Passive behavior (PA)	Students simply listen and read or browse the content of the textbook.	Simply listening and watching the teacher.
Active behavior (A)	Students do some writing on the learning sheet or can follow the instructions to complete the teaching task.	Students begin to think about and briefly discuss marking suitable locations for anti-mosquito sprayer on their learning sheets.
Active discussion (AD)	Students participate in group or class discussions, such as allotting jobs and checking procedures	Student A: Who is responsible for giving the presentation on stage?

	following the instruction of the teacher.	Student B: I can
Constructive behavior (C)	Students go online to search for and analyze information, assemble needed parts, or write programs.	Students think about how to write a program and search for information on the Internet.
Constructive discussion (CD)	While students participate or discus in group, they work and think deeply or integrate information.	Student A: Do we need to add a timed automatic spraying device to the anti-mosquito sprayer? Student B: "I think we can. But how often should it be set to spray?"
Interactive behavior (I)	When students participate constructively in group activities, they may discuss more complex learning materials with specific group members or the teacher.	Student's Question: "Teacher, can I use this method to write the program?" Teacher's Response: "Sure! Coming up with your own ideas is impressive."
None (N)	Students doing something unrelated to the classroom	Chatting about non-course related content

Table 2. *A Coding Framework for Teacher Behavior in the Classroom*

Code	**Definition**	**EXAMPLE**
Teacher-centered		
Showing (T.S)	Teacher shows slides or products.	Teacher showing finished products or parts
Teaching (T.T)	Teacher explains concepts or principles to the class.	Explain what the five steps of design thinking are
Student-centered		
Answering questions (T.A)	Teacher answers students' questions.	Student's Question: "Teacher, is this assembly correct?" Teacher's Response: "You've got it the wrong way, flip it over and it'll be right."
Giving feedback (T.F)	Teacher gives feedback to the class, a group or a student for their works or ideas.	The teacher provides encouragement for the project reported by the student, along with areas that can be improved.
Asking questions (T.Q)	Teacher asks students questions and expects them to respond.	Teachers ask: Where is the suitable place to put anti-mosquito sprayer in the school?
Seeing & Listening (T.SL)	Teacher observes students or listens to their discussion	Teacher observing students assembling parts
Transitional		
Instruct (T.I)	Teacher instructs to illicit certain student behaviors or offer general principles about how to process tasks.	Teacher says, "Now you have five minutes to come up with three solutions for each group.

Session	Student	observer	Time	Student Behaviors							Teacher Behaviors						
				AD	A	PA	N	CD	C	I	T.A	T.F	T.I	T.Q	T.SL	T.S	T.T
D1	D1.1	Karina	14:28	0	0	0	1	0	0	0	0	0	1	0	0	0	0
D1	D1.1	Karina	14:29	0	0	1	0	0	0	0	0	0	0	0	0	0	1
D1	D1.1	Karina	14:30	0	0	1	0	0	0	0	0	0	0	0	0	0	1
D1	D1.1	Karina	14:31	0	0	1	0	0	0	0	0	0	0	0	0	0	1
D1	D1.1	Karina	14:32	0	0	1	0	0	0	0	0	0	0	0	0	0	1
D1	D1.1	Karina	14:33	0	0	1	0	0	0	0	0	0	0	0	0	0	1
D1	D1.1	Karina	14:34	0	0	1	0	0	0	0	0	0	0	0	0	0	1
D1	D1.1	Karina	14:35	0	0	1	0	0	0	0	0	0	0	0	0	0	1
D1	D1.1	Karina	14:36	0	0	1	0	0	0	0	0	0	0	0	0	0	1
D1	D1.1	Karina	14:37	0	0	1	0	0	0	0	0	0	0	0	0	0	1

Figure 1. Presented through the data table recorded by COPIE-STEM

3.2.2 Observer Training

Prior to formal observation, each observer needed to undergo a two-hour training session focused on familiarizing themselves with the coding behaviors of both teachers and students. The inter-rater reliability between observers, measured using Sokal and Michener coefficients (SMC), is 0.92 (Hsiao et al.,2022). A total of three observers were responsible for collecting the student-teacher data for this study. Each observer primarily recorded the behaviors of a target student and the teacher every minute using COPIE-STEM (see Figure 2).

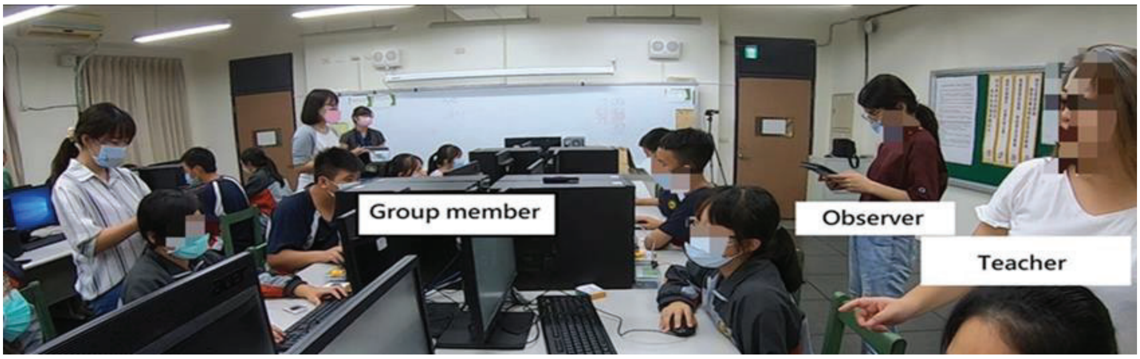

Figure 2. An Example of the Classroom Observation

3.3 Data Analysis

This study firstly utilized a coding and counting approach to calculate the proportional distribution of student and teacher behaviors over the course of six weeks. Subsequently, for the second question, we utilized ENA web tool (http://www.epistemicnetwork.org/) to investigate the network models for the data of teachers and students throughout these six weeks of instruction. ENA uses a sliding window to segment content-related behavioral data into sections called "stanza". By calculating the co-occurrence of behavioral data, ENA constructs epistemic networks to comprehend the interactions between these behaviors. In ENA, coded elements serve as nodes within the epistemic network. The thickness of inter-nodal links in these networks represents the frequency of co-occurrence between elements. A thicker link indicates a higher frequency of co-occurrence between elements. For our second research question, we have chosen "student" as the analytical unit. The stanza size is set at 4, and the codes encompass student behaviors and teacher behaviors. This configuration allows us to observe the epistemic network model summarizing the behavioral interaction in the course. As for the third research question, we have selected "week" and "student" as the analytical units with the other settings remaining unchanged. In this context, we focus on observing and comparing the trends and changes in the centroids of the course each week.

4. Results

4.1 RQ1: What is the distribution of individual behavior code frequencies for teachers and students in each week?

Table 3 presents the frequency distribution of student and teacher behaviors over the six weeks of the course, in which W1 represents the first week and so forth. Passive behavior (PA) constituted the highest proportion almost every week (63%, 40%, 61%, 41%, 38%, 26% for W1 to W6, respectively), except for the last week (W6) where the proportion of Constructive behavior (C) slightly surpassed that of Passive behavior (PA). Based on the results for the first three weeks, we found that most behaviors concentrated on Passive behavior (PA), Active behavior (A), and Active discussion (AD). In contrast, during the last three weeks, Constructive behavior (C) had notably increased compared to the previous weeks. Finally, throughout the six weeks, Interactive behavior (I) consistently remained the lowest proportion among all the behaviors observed across six weeks (0%, 3%, 1%, 3%, 2%, 8% for each respective week).

Table 3. *Frequency Distribution of Student Engagement Behavior*

	W1		W2		W3		W4		W5		W6	
	(F)	(%)	(F)	(%)	(F)	(%)	(F)	(%)	(F)	(%)	(F)	(%)
PA	83	63%	59	40%	83	61%	55	41%	62	38%	37	26%
A	26	20%	24	16%	15	11%	7	5%	26	16%	9	6%
AD	7	5%	36	24%	15	11%	28	21%	15	9%	18	13%
C	1	1%	3	2%	8	6%	24	18%	37	23%	38	27%
CD	3	2%	3	2%	3	2%	9	7%	16	10%	15	11%
I	0	0%	4	3%	2	1%	4	3%	4	2%	12	8%
N	12	9%	19	13%	10	7%	8	6%	4	2%	13	9%
Total	132	100%	148	100%	136	100%	135	100%	164	100%	142	100%

Table 4 shows the frequency and proportion of teacher behaviors during the six weeks. In the first and third weeks, the most frequently occurring teacher behavior was Teaching (T.T), accounting for 42% and 38% respectively. The remaining weeks predominantly featured the teacher behavior of Seeing & Listening (T.SL), with proportions of 24%, 44%, 36%, and 35% across the respective weeks. Notably, the behavior of Answering questions (T.A) was nearly negligible, approaching 0% for all six weeks. As frequencies and percentages alone cannot explain complex co-occurrences (Csanadi, 2018), we subsequently employed ENA to gain a deeper understanding of the relationship between student and teacher behaviors within the six weeks of the course.

Table 4. *Frequency Distribution of Teacher Behavior*

	W1		W2		W3		W4		W5		W6	
	(F)	(%)	(F)	(%)	(F)	(%)	(F)	(%)	(F)	(%)	(F)	(%)
T.A	0	0%	1	0%	1	0%	0	0%	1	0%	0	0%
T.F	3	2%	54	21%	19	8%	36	15%	15	6%	46	19%
T.Q	7	4%	40	16%	21	9%	31	13%	11	4%	11	4%
T.SL	2	1%	60	24%	53	22%	102	44%	87	36%	87	35%

T.I	53	29%	51	20%	50	21%	39	17%	49	20%	39	16%
T.S	39	22%	15	6%	5	2%	6	3%	11	4%	9	4%
T.T	76	42%	31	12%	90	38%	20	9%	71	29%	56	23%
Total	180	100%	252	100%	239	100%	234	100%	245	100%	248	100%

4.2 RQ2: What does ENA portray in the overall contextual relationship between teacher and student behaviors throughout the six-week course?

From Figure 3, the epistemic network graph of all the student and teacher behaviors during the six weeks is presented. Singular Value Decomposition (SVD) was utilized to project nodes onto a space with two-orthogonal dimensions (SVD1 and SVD2) by maximizing variance within the data. The positions of nodes in the SVD1 x SVD2 space explain the relationship of the behaviors of interest and the meaing of the dimensions or quadrants (Shaffer et al., 2016).

The first dimension (SVD1) of the ENA space explained 30.8% of the variance within the ENA space, while the second dimension (SVD2) explained 21.6% of the variance. In the first quadrant, there were Constructive behavior (C), Constructive discussion (CD), and Interactive behavior (I), alongside the teacher behavior Seeing & Listening (T.SL). The second quadrant encompassed teacher behaviors Answering questions (T.A), Teaching (T.T), and Instruct (T.I). The third quadrant featured Active behavior (A), Passive behavior (PA), None (N), as well as two teacher behaviors, Showing (T.S) and Asking questions (T.Q). Lastly, the fourth quadrant contained Active discussion (AD) and Giving feedback (T.F).

Overall, the left half of the space predominantly featured teacher-centered behaviors (e.g., T.T and T.S) and passive engagement behaviors (e.g., PA), whereas the right half showcased more active engagement behaviors (e.g., AD, CD, C, etc.) and student-centered teacher behaviors (e.g., T.SL and T.F). We also found that higher level engagement behaviors concentrated on the upper part the space, while lower level engagement behaviors concentrated on the lower part of the space. Continuing, by observing the node sizes, we identified that the more frequently occurring behaviors were T.T, T.I, T.SL, and PA. The connection coefficients between these four nodes were as follows: PA-T.T (0.27), PA-T.I (0.24), PA-T.SL (0.24), T.I-T.SL (0.22), T.I-T.T (0.21), and T.SL-T.T (0.21). Lastly, it's noticeable from Figure 3 that T.A had minimal associations with other behaviors.

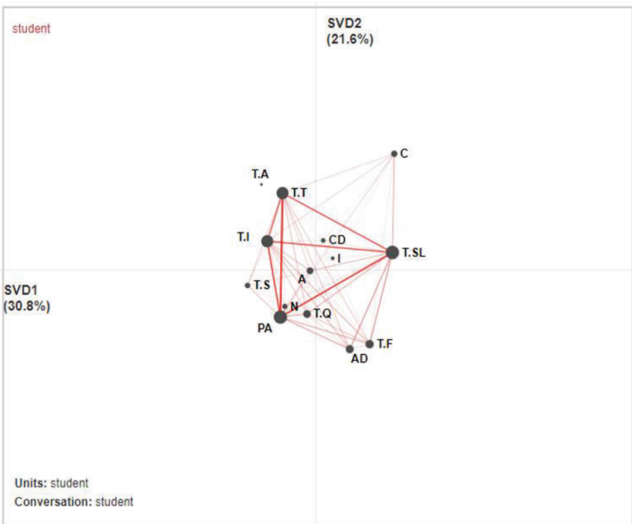

Figure 3. Epistemic Network for the Six-Week Course

4.3 RQ3: Does the ENA method identify subtle differences in teacher and student behaviors across the six-week course?

In order to further understand the differences between each week's courses, we utilized ENA to display where the centroids of each week are distributed within the overall epistemic network (Figure 4). Each week was represented using a different color with an arrow indicating the temporal development. Notably, there was a gradual shift from the lower left to the upper right.

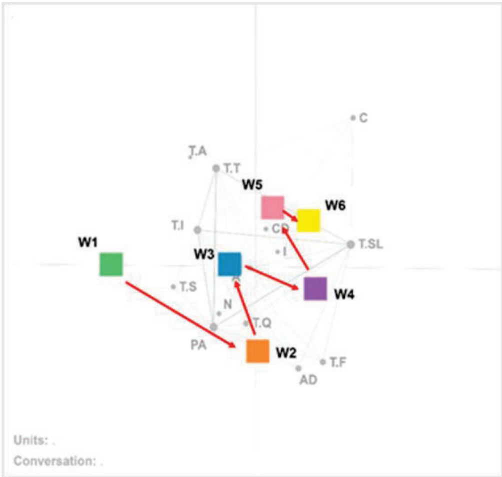

Figure 4. Epistemic Network Centroids of the Each Week

Figure 5 presents the network graph for each week's course. It's noticeable that the courses in W1, W2, and W3 were more associated with passive and active student behaviors, while W4, W5, and W6 exhibited an increased proportion of constructive and interactive behaviors. The strength of connections between nodes evolved from the initial prominent PA-T.T link to the subsequent more pronounced links of various behaviors and T.SL, partialy confirming the developmental trace that ended at the first quadrant (see Figure 4).

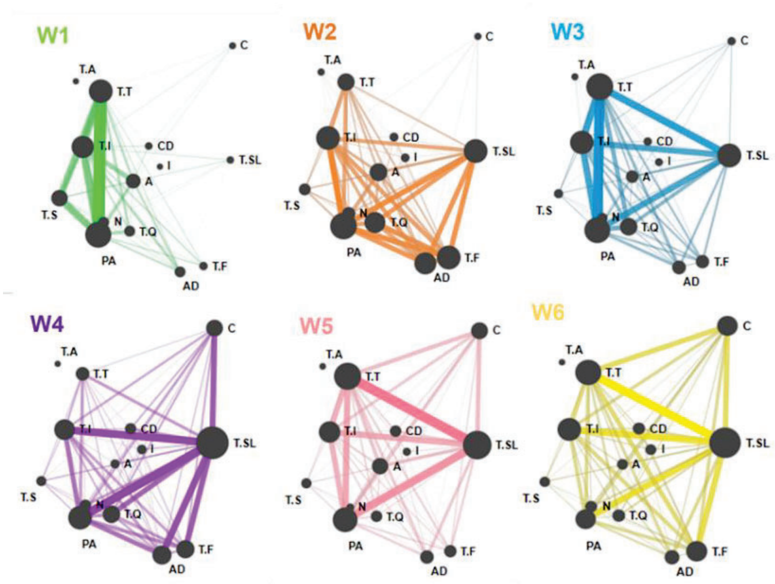

Figure 5. Epistemic Networks of the Each Week Course

5. Discussion & Conclusion

Our study investigates the relationship between student engagement and teacher instructional approaches in a six-week STEM-PBL course. We used coding and counting techniques to analyze student and teacher behaviors, and we applied ENA for in-depth class analysis. Initially, we observed that Passive behaviors(PA) are prevalent in the course, indicating students' primarily passive engagement. Additionally, we identified strong associations between specific behaviors via ENA analysis. For instance, when teachers delivered content and demonstrated materials, students tended to passively listen, reflecting traditional teacher-centered classroom dynamics (Serin, 2018).

Using ENA to track weekly student and teacher behaviors, our study identified a shift from the lower left to the upper right on the graphs. A closer look at individual network graphs revealed an initial focus on student passive engagement behavior and teacher-centered instruction, gradually evolving into increased constructive engagement and student-centered approaches. This indicates a growing diversity in classroom dynamics over time, with teachers adjusting their instructional approaches, and students moving to different levels of cognitive engagement accordingly. These findings are consistent with our expectations and parallel the results observed by Akiha et al. (2018) in their study of secondary school STEM courses. The reduction in teacher-centered practices like lecturing and increased emphasis on active learning practices such as teacher guidance and student group collaboration align with their findings as well.

In summary, regardless of whether the instruction is teacher-centered or student-centered, passive student engagement behavior is surprisingly prevalent. In order to diminish passive student engagement, teachers can find a balance between teacher-centered and student-centered instruction while incorporating thoughtfully crafted activities. Implementing impactful instructional techniques, such as actively questioning students about high-level thinking, can result in improved student learning outcomes (Hsiao & Chang, 2023). Furthermore, the insights gained from ENA analysis results can assist educators in evaluating whether their courses are proceeding as planned or expected, thereby enhancing student learning outcomes.

This study also has some limitations. We collected data using the COPIE-STEM classroom observation protocol, which records data every minute, possibly missing some details. Additionally, our research covered only the first six weeks of the STEM-PBL course, which may not apply universally. Future studies should observe more extended programs for a broader perspective. Furthermore, while ENA helped explore teacher-student behavior relationships, we haven't fully explained why certain behaviors correlate strongly. Future investigations may require video analysis or course plan examination to clarify these associations. Overall, this study employed ENA to analyze STEM-PBL course dynamics but offers room for refinement and deeper exploration due to the mentioned limitations.

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