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Development of a Method to Understand How Students Navigate Confusion in a Chemical Engineering Thermodynamics Studio

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Introduction

Confusion is an integral part of the learning process, but it can often spark negative affect. Students may be compelled to avoid confusion as it can prompt negative self-perceptions around misalignment between the preconceived notions of experiencing confusion and being a "good" student [1], [2]. Instructors can view confusion as a negative aspect of classroom delivery, favoring clear lectures and neatly solved example problems [3]. However, confusion has been shown to be beneficial to learning [4], [5]. Additionally, in authentic engineering work, confusion is integral to making progress [6]. To better design engineering learning environments where students can both engage with and learn to tolerate confusion, we must better understand how confusion arises in context. In the classroom setting, small groups provide a vehicle for supporting students through confusion and for allowing researchers to study their responses [7], [8]. Thus, we focus on small-group collaborative work to understand group sensemaking practices and the role of confusion therein.

This paper describes the work done as part of a larger NSF-funded project that aims to understand ambiguity, uncertainty, and confusion in chemical engineering, introductory engineering, and physics courses. We define confusion as the cognitive and affective response to encountering an impasse while learning. For this work, audio- and video- data were collected from three consenting groups of students in a second-year thermodynamics studio in a chemical engineering department across 14 weeks. Studios meet for 50 minutes. They supplement the lecture by giving students the opportunity to tackle challenging, open-ended problems while working in small groups [9].

Here, we present the development of a methodological approach to investigate these recorded data. To understand confusion – a dynamic and complex affect – as well as its role in student-student and student-instructor interactions, we need a data coding and visualization method that can track discursive practices, use of resources, instances of hedging, and episodes of confusion across time. Discourse analysis [10] was used to generate a codebook. Timelines have been used in many fields to convey a narrative about sequences of events [11]. However, to our knowledge, they have not been used to understand confusion and its role in small-group collaborative work. In this paper, we detail our development of a qualitative codebook and timelines as a method for analyzing confusion.

Background

Confusion

Confusion has been defined in a variety of ways, including, but not limited to an epistemic emotion, a mental state, or an affect [5], [12]. We define confusion *as the cognitive and affective response to encountering an impasse when learning*. Taking a constructivist lens, the cognitive process of learning involves continuously incorporating new knowledge into a learner's mental models or schema [8]. However, when there is a discrepancy [5], [13], [14] between the known information and a challenging new information task, confusion can arise alongside other emotions like discomfort, insecurity, and fear [15], [16]. From a social practices perspective, confusion could also arise from incongruent participation in the knowledge and social practices of the discipline since members of a group often formulate coordinated action that is dependent on shared understanding of valued practices and goals [17], [18].

Researchers have previously reported positive correlations between confusion and learning gains while other measures of student learning show that working through confusion is productive for students [1]. D'Mello et al. [5] extend this proposition, stating that confusion can become a signal for deeper thinking and higher order reasoning. However, to work through confusion, students must tolerate and be resilient to the often-negative affect associated with confusion. Students who can tolerate the ambiguity and uncertainty that lead to confusion have been shown to have improved creativity, be less averse to risk-taking, and gain skill-based reasoning [15], [19] - [23].

The design of learning environments is crucial to helping students productively manage confusion and other negative affect associated with learning. Instructors play a large role in fostering tolerance and resilience to confusion. They should design tasks and cultivate learning environments that allow for constructive ambiguity but do not lead to a level of confusion that may frustrate students to the point where they are overly anxious or upset to deter learning [3], [24], [25]. Below we detail one strategy to foster inclusive, safe environments for learners to engage students in tolerable amounts of confusion – small-group collaborative work.

Small-Group Collaborative Work

Small-group collaboration has been shown to improve students' conceptual understanding, engagement with the material, and problem-solving skills [7], [26]. This study specifically looks at small-group collaborative work in a *studio* setting. The studio architecture is designed to facilitate active learning by giving students time outside lectures to engage with course material in small groups through challenging problems. Studio sessions are typically led by a graduate teaching assistant (GTA) and an undergraduate learning assistant (LA) and differ from typical recitations in that students spend the entire studio solving problems with their groupmates [9]. The studio setting studied here is designed to have students engage in a tolerable level of ambiguity and uncertainty where the instructor's role is to facilitate engagement, productive discussion, and sense-making but not to show students how to solve the problems or to provide their own thinking.

Regarding the formation of engineers, professionals regularly work in teams and deal with tasks that typically do not have one correct answer, so managing confusion becomes essential. An aspect of productive disciplinary practice is that when faced with a challenging task that doesn't necessarily have a correct answer, one can reason through it, not be afraid of potential failure, and have the resilience to continue if something doesn't work as expected [27]. However, typical assessments in postsecondary engineering US classrooms center on single-right-answer forms of engineering, emphasizing products of learning and individualism rather than co-constructed learning [6], [7], [28]. Studies evaluating confusion in engineering classrooms can help instructors and researchers design more effective learning environments that better prepare students for postgraduate careers in industry or the academy.

Timelines as a Narrative Tool

Timelines have been used in numerous contexts in fields like journalism, sociology, and history to communicate sequences of events and as a narrative tool [11]. In design education research, Atman [29] reports on the use of timelines to compare how novices and experts engage in the engineering design process. Timelines provide a unique representation of design signatures that have time as an explicit element and can make an abstract concept like design more *concrete* [29], [30]. Similarly, they note that that timelines are visually appealing and "stick" in people's memories further improving the transferability of the work [30]. Our motivation to use timelines comes from our interest in understanding the dynamics between students' discursive practices, use of resources, and instances of hedging, before, during, and after episodes of confusion, necessitating a data visualization technique that accounts for time.

Conceptual Framework

We view this work through the lens of situated learning, which asserts that knowledge is distributed across elements (e.g., time, space, society, etc.) of an individual's environment. It is through our interactions with these elements that we make meaning and construct knowledge [31] - [35]. Situated learning posits that social interactions serve as sites of learning and knowledge production. As Johri et al. [33] state:

> In this view, then, learning takes place not through transmission of abstract knowledge, but through engagement in the "knowledgeable skills" that are realized in the everyday activities of a community; that is, people become good at the practices that they routinely participate in, gaining understanding of how to engage successfully under varying conditions by flexibly adapting their performance to the contingencies of particular occasions. (p. 48)

Understanding how learning unfolds as students negotiate confusion in small-group collaborative work can help instructors and researchers understand how students make meaning of complex concepts in STEM subjects and their ability to uptake disciplinary concepts. Through qualitative coding and timelines, we operationalize these concepts to understand how students co-construct knowledge through different discursive practices while negotiating confusion.

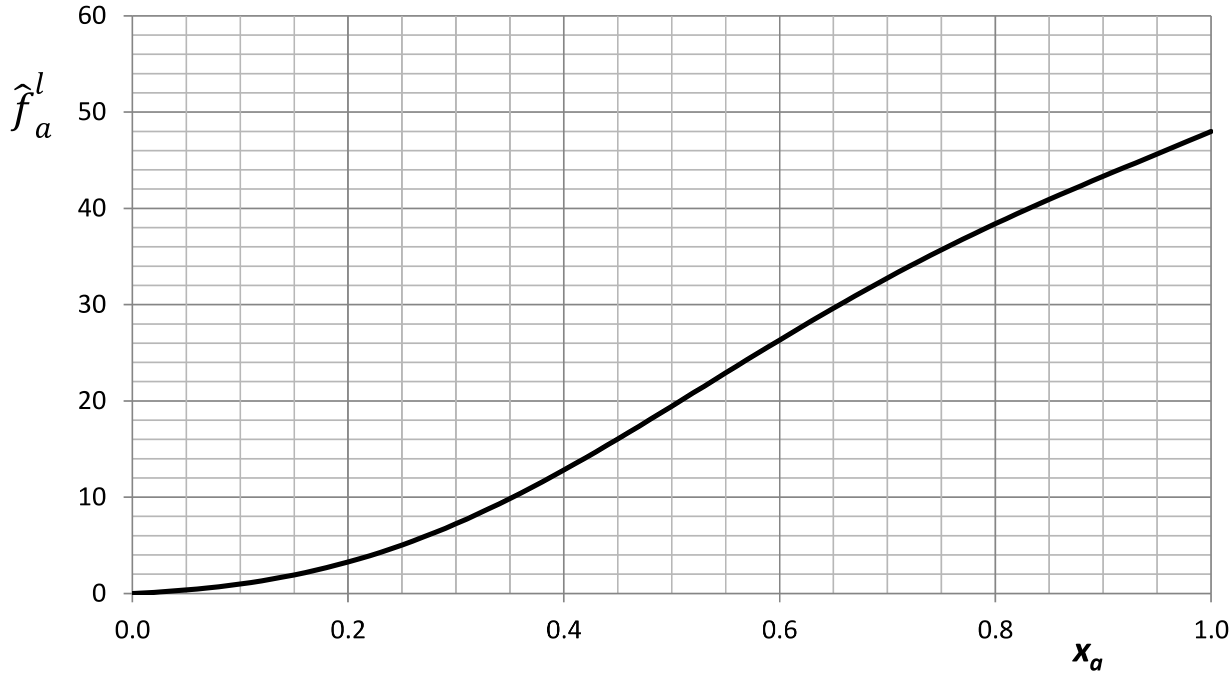
Methods

Research Design

This work is part of a larger NSF-funded Growing Convergent Research grant studying ambiguity, uncertainty, and confusion in postsecondary STEM contexts. This research was approved by the Institutional Review Board. Video data were collected of students completing small-group collaborative tasks for all 14 weeks of studio. We then conducted a discourse analysis on three groups completing the Henry's law activity shown in Fig. 1. This activity asks students to connect concepts in thermodynamics (e.g., fugacity, infinite dilution, non-ideal solutions, etc.) with mathematical (e.g., manipulating equations, limits, etc.) and graphical representations and reasoning skills (e.g., slope). Our motivation to study this problem also stems from the literature that notes the difficulty for students to understand fugacity [36].

Question 1

Consider a binary mixture of species *a* and *b*. A graph of the fugacity of species *a* in the liquid pha mole fraction of *a* is shown below. You will also have a full-page chart to work on as a group.



a. Draw a line that shows what the fugacity would be in an ideal solution, $\hat{f}_a^{ideal}$, vs. x_a.
b. What is the value of the Henry's law constant? Show how you calculate it from this graphical representation on the same chart.
c. Calculate the activity coefficient at a mole fraction x_a = 0.4.
d. Are the like or unlike interactions stronger? Explain.

Fig. 1. Problem statement for Henry's Law activity. See Appendix A for problem solution.

Participants and Settings

All participants were consenting students in an undergraduate chemical engineering thermodynamics course at a suburban mid-sized, research-intensive (R1) institution. Demographic characteristics for the institution are shown in Table I [37] for context. The three recorded groups typically include three students each. However, this specific week, two of the groups had one student missing. Pseudonyms are provided in Table II. The instructor-of-record is a tenured faculty member in chemical engineering with multiple years of experience in teaching thermodynamics. The studio is led by a graduate teaching assistant (a chemical engineering doctoral student) and a learning assistant (a chemical engineering undergraduate). On some occasions the instructor-of-record joined the studio. We refer to all three of them singularly as "instructor" as this study is concerned with student-student and student-instructor interactions.

TABLE I
DEMOGRAPHIC CHARACTERISTICS FOR INSTITUTION IN THIS STUDY

Demographic Characteristic		
Average Annual Cost		~ $35,000
Undergraduate Population		~ 7,000
% of students who receive income-based federal Pell grant		12%
Student-to-faculty ratio		10:1
Student Body Race/Ethnicity	American Indian/Alaska Native	0%
	Asian	17%
	Black	7%
	Hispanic	10%
	Native Hawaiian/Pacific Islander	0%
	Non-resident alien	12%
	Two or more races	8%
	Unknown	4%
	White	42%

TABLE II
PSEUDONYMS FOR GROUP PARTICIPANTS

Group	Pseudonyms
1	Beth, Anna, and Harris
2	Lucas and Gertrude
3	Pam and Jan

Data Collection

Three groups, each with three students were recorded during studios throughout the 14-week term. Some students also participated in an additional part of the study where they wrote weekly journals reflecting on their confusion and completed 2-3 interviews. All data was anonymized and stored on a secure Box drive. Recordings were transcribed using an IRB-approved tool called Sonix [38]. Author 1 then edited all transcripts for accuracy.

Data Analysis

Discourse analysis [10], [39] was used to analyze transcripts. To develop a coding scheme, Authors 1 and 2 started by analyzing an episode of a transcript looking for emergent ideas regarding student-student and student-instruction interactions. After initial coding on Google Sheets, Authors 1, 2, and 3 then narrowed down the codebook and generated four categories of code:

- **Episode Codes** – Codes that were applied to entire episodes. An episode is a set of coherent sequences that have a unifying theme or pattern and has a defined beginning and end [10].
- **Turn Codes** – A “turn” is a unit of analysis, defined as a single, coherent contribution by a speaker [10]. These codes described discursive practices on a more granular level.
- **Search Codes** – Codes applied to a turn when specific words appeared (e.g., “Yeah” for Affirm/Confirm or “I/We know” for Know)
- **Confusion Codes** – Codes that were applied during episodes of confusion.

Our method for determining episodes of confusion centered on finding instances where students explicitly expressed confusion through markers of incongruence in knowledge structures or, implicitly, through hedging and other tonal/bodily cues [1]. We differentiated confusion from other forms of student interactions as we looked for cases where students were both stuck during the problem-solving process *and* showed signs of an affective response to this. An episode of confusion includes: 1) the triggering event for confusion, 2) the turns students are confused, and 3) the exiting event that shifts them out of confusion to other forms of interaction. Episodes of confusion were not limited to a specific outcome. For example, during confusion students could have guessed on how to solve the problem or engaged in deeper conceptual reasoning. The episode was included as long as the affect expressed by students was related to being stuck while co-constructing knowledge. As this work is part of a larger project studying confusion in different STEM contexts, the authors consulted with members of the project team to check consistency for these classifications. Fig. 2 shows a visualization of how we organized codes and code groups while iterating through them.

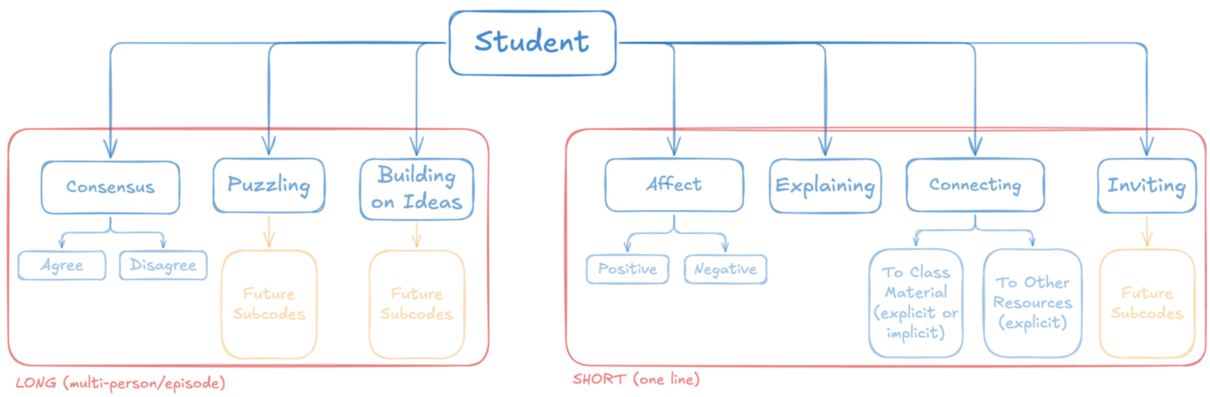


Fig. 2. Organization of codes.

Authors 1 and 2 coded a new episode from a different group to determine interrater reliability. A Cohen's kappa of 0.8 for episode codes and 0.7 for turn codes were achieved, noting substantial agreement for both. Author 1 then coded all three transcripts while consulting with Author 3. Fig 3. shows an example of coding done in Google Sheets. Episodes are separated by the gray or orange alternating colors. Timelines were developed by Authors 1 and 2 on Google Sheets, where codes were each given a row and every column represented a line.

	STUDENT CODES						INSTRUCTOR CODES	CONFUSION
	HAND CODED		SEARCHABLE			HAND CODED	HAND CODED	HAND CODED
Line	Episode Codes	Med Codes	Confirm/Affirm	Confusion Explicit	Know/Not Know	Resources	Instructor	Student
5	Puzzling	Connecting: in class, Inviting						Confused
6		Connecting: in class		Confusion		Notes		Confused
7		Connecting: in class				Notes		Confused
8		Explaining	Affirm			Notes		Confused
9		Connecting: in class				Notes		Confused
10		Connecting: in class, Explaining	Affirm			Notes		Confused
11	BLANK							Confused
12			Affirm	Confusion				Confused
13								Confused
14								Confused
15				Confusion				Confused
16								Confused
17	Puzzling, Consensus: Agree	Connecting: in class				Notes		Confused
18						Notes		Confused
19		Connecting: in class				Notes		Confused
20		Connecting: in class				Notes		Confused
21		Connecting: in class, Explaining	Affirm			Notes		Confused
22						Notes		Confused
23		Explaining, Connecting: in class	Affirm			Notes		Confused
24		Explaining, Connecting: in class				Notes		Confused
25	Consensus: Agree, Puzzling							

Fig. 3. Example of the final coding done on transcripts in Google Sheets.

Limitations

Complete demographic information was not collected. Some of the audio is quiet or has background noise, making it difficult at times to understand what participants say. This is noted as "((inaudible))" in the transcript text. The data was collected at a R1, mid-sized institution within a thermodynamics class, which may limit application of findings to other contexts. However, we view these timelines as a part of our process to develop a robust methodology for understanding student confusion that we hope could be applied to other contexts.

Findings

Group Timelines

Figs. 4, 5, and 6, show the timelines generated for each group based on our qualitative coding. The horizontal axis is the temporal dimension, and the vertical axis is the code and code group. Codes in the timeline were organized into four themes: **cohesion, reasoning, resources, and hedges**. Table III details the themes and associated codes.

- **Cohesion:** Coherence related to group ideas and affect.
- **Reasoning:** Different discursive practices associated with thinking through the problem.
- **Resources:** Material tools or help from the instructor.
- **Hedges:** Short words or phrases that help to soften a statement or convey uncertainty.

TABLE III
THEMES AND ASSOCIATED CODES TRACKED IN THE TIMELINES

Theme	Code	Definition
Cohesion	Affirm	Explicit mentions of "Yes" or "Yeah"
	Agree	Student(s) agree on reasoning.
	Disagree	Student(s) disagree about reasoning.
	Pos Affect	Student(s) express positive affect about the problem, studio, school, life, etc. This also includes body language or other physical cues that may indicate joy, amazement, or wonderment.
	Neg Affect	Students express negative affect about the problem, studio, school, life, etc. This also includes body language or other physical cues that may indicate duress.
	Know	Students mention something that they know (comes with an "I know… " or "we know …").
	Not Know	Students mention something that they don't know (comes with an "I don't know… " or "we don't know …").
Reasoning	Explain	Student makes a claim and provides an explanation, which is typically indicated by "because."
	Connecting: In Class	Student connects to an idea from the class.
	Connecting: Out Class	Student connects to an idea outside of class.
	Puzzling	Students puzzle through concept(s) or parts of the question.
	Building on Ideas	The student takes the peer's idea and expands. This means they take a part of their peers' idea and explicitly add something new related to it. Students take multiple ideas and coordinate or synthesize them.
Resources	Instructor Present	Students interact with any member of the instructional team.
	Problem Statement	Students interact with the problem statement. This includes reference to any graphs or figures in the problem statement.
	Whiteboard	Interactions with whiteboard.
	Notes	Students interact with class notes. This includes reference to class notes.
	Internet	Students consult internet for information, to seek an answer for a question, or clarification.
Hedges	"Think"	Explicit mention of "think" to soften a statement.
	"Feel"	Explicit mention of "feel" to soften a statement.
	"Seem"	Explicit mention of "seem" to soften a statement.
	"Might"	Explicit mention of "might" to soften a statement.
	"Could"	Explicit mention of "could" to soften a statement.
	Confusion Explicit	Explicit mention of confusion.
	Inviting	An explicit cue used to both soften statement and ask others to contribute. (e.g., "Perhaps?")

Group 1's timeline is shown in Fig 4. Group 1 was comprised of three students who participated relatively equally. This group discussed the problem the longest, had the longest interaction with the instructor (Instructor Present), and seven episodes of confusion (shaded). When discussing links to specific codes, we bold them in the text.

Shortly after the Group 1 reads the problem statement, they begin puzzling while **connecting in-class** ideas and **explaining** how they operationalize those ideas. Once they begin **building on ideas**, they enter a brief episode of confusion (1.1) where there is a notable absence of **explaining** and **connecting to in-class** ideas. As they stop **building on ideas** and begin

puzzling, they enter another episode of confusion (1.2) where they use more **hedges** compared to before. A member of the **instructional team** is present mid-way through the episode which also co-occurs with the group **building on ideas,** pointing to the instructor shifting group reasoning practices. Episode of confusion 1.3 begins shortly after 1.2 where the instructor is still present and there is **puzzling** and **building on ideas**. Exiting 1.3, there is a long stretch where the students interact with the instructor and the reasoning shifts from **puzzling** to **building on ideas,** further shown by the increased density of **explaining** codes indicating that students are reasoning through the problem using **in-class** resources and possibly engaging in sensemaking. Episode of confusion 1.4 begins as the instructor is still there and both **puzzling** and **building on ideas.** After the instructor leaves after 1.4, there is a brief period where there is not evidence of reasoning and then the group enters episode of confusion 1.5, which includes some negative affect and puzzling, pointing to some frustration with their reasoning. Episode 1.5 ends as another member of the instructional team enters the conversation where the group will continue puzzling. Episode 1.6 begins with the group both **agreeing** and **disagreeing**, indicating they may be experiencing a lack of cohesion while **connecting in-class** and **explaining**. Finally, they enter episode 1.7 where the group is again both **agreeing** and **disagreeing**. The group **puzzles** and **builds on ideas** to finish off solving this problem. Throughout problem solving, the group doesn’t use many material resources.

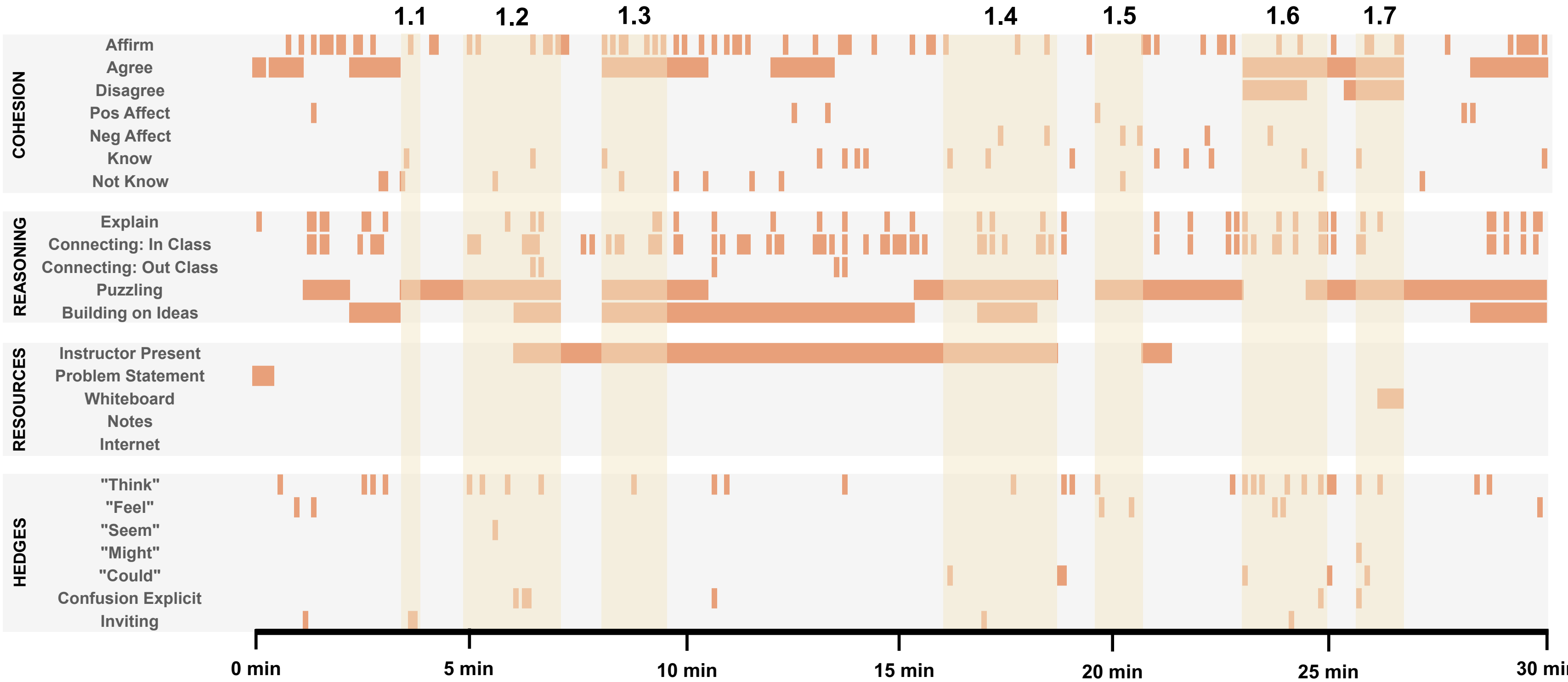


Fig. 4. Timeline for Group 1. Areas shaded in light yellow indicate episodes of confusion.

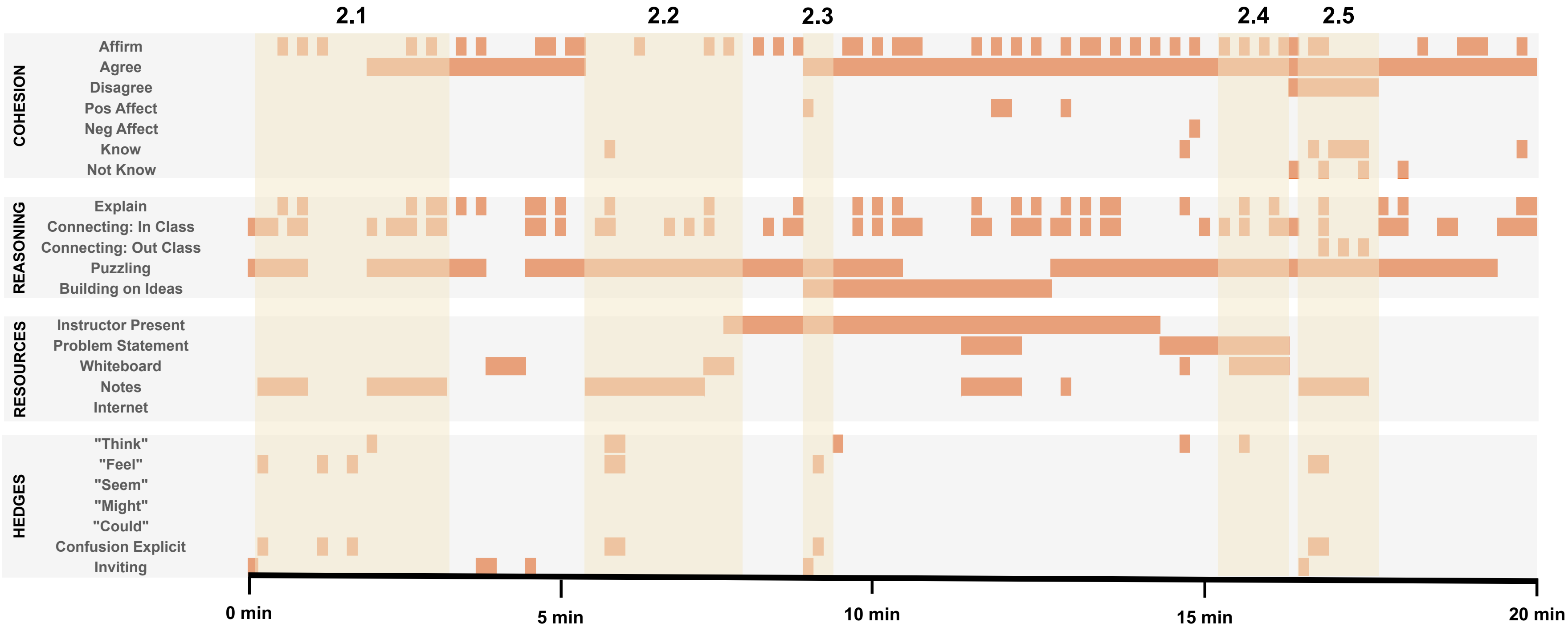


Fig. 5. Timeline for Group 2. Areas shaded in light yellow indicate episodes of confusion.

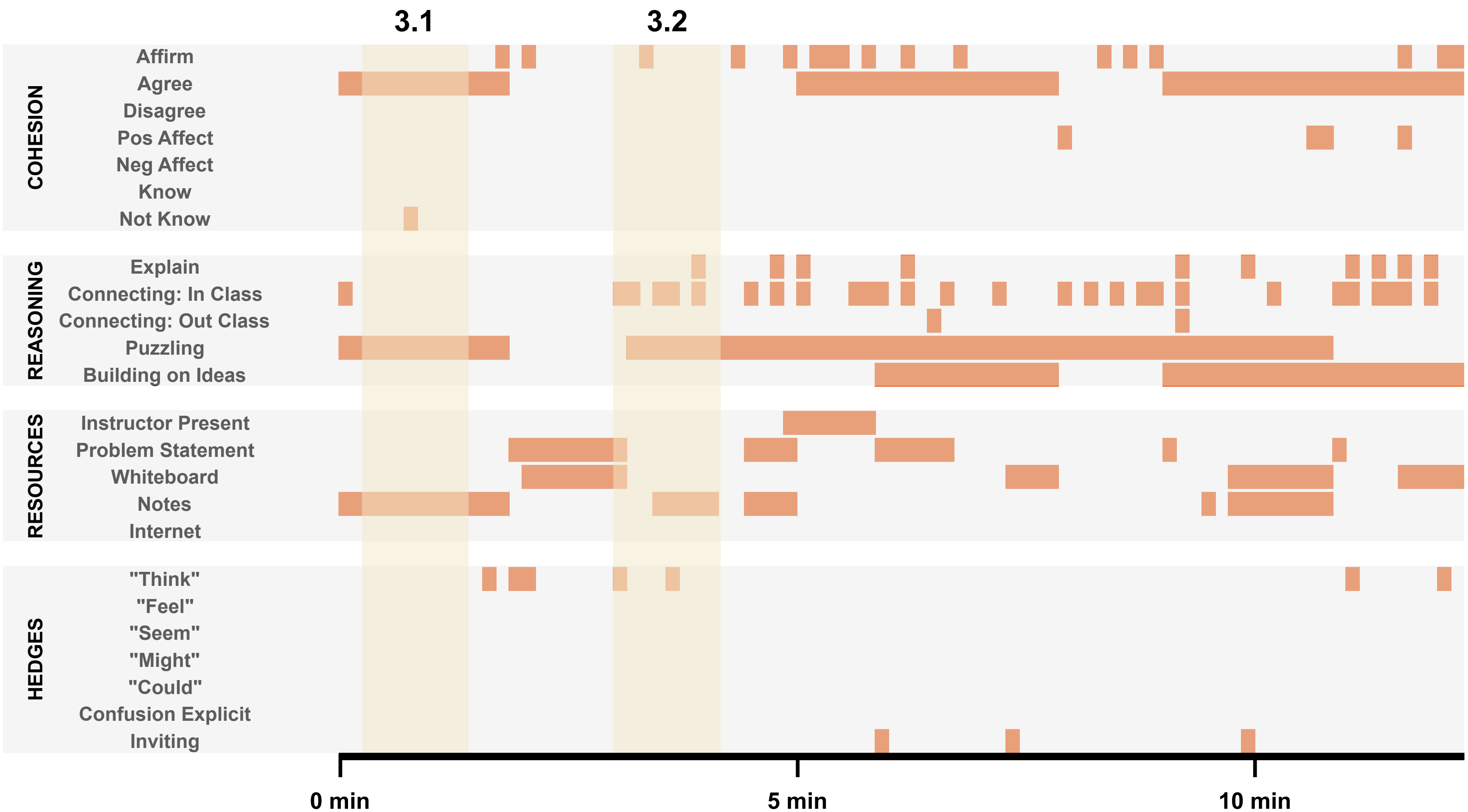


Fig. 6. Timeline for Group 3. Areas shaded in light yellow indicate episodes of confusion.

Group 2, shown in Fig 5, was comprised of two students who participated relatively equally. This group also had a substantially long interaction with the instructor (Instructor Present) and five episodes of confusion (shaded). Group 2 almost immediately begins in experiencing an episode of confusion (2.1) as they look to the **notes** to **connect in-class** concepts and **explain** their reasoning. After a brief pause within the same episode where there is no puzzling or consulting of notes, they begin **puzzling** again and seem to come to an **agreement** about their **explanations involving connections to class materials**. After episode 2.1, there is a notable gap before they enter the next episode of confusion where they seem to be sensemaking. However, episode 2.2 begins when they consult the **notes** again, possibly showing that the content in the notes is not the most productive during this prolonged phase of **puzzling**. Episode 2.2 ends shortly after a member of the **instructional team** enters the conversation. There is a pause in confusion, but when the group begins **building on ideas alongside puzzling**, there is a brief instance of confusion where **hedges** are present (2.3). Continuing to work with the instructor they shift from **building on ideas** to **puzzling** where the presence of **explaining** and **connecting to in class material** indicate sensemaking. Episodes of confusion 2.4 and 2.5 occur close to one another where the group is **puzzling** and during episode 2.5 their prolonged phase of **agreement** encounters brief **disagreement**. They end the problem with more **puzzling**.

Group 3, shown in Fig. 6, spent the least amount of time on the problem and had the least substantial interaction with the instructor (Instructor Present). The group was comprised of two students, and one student appeared to dominate the first half of the Henry's Law activity. Group 9 also begins the problem with an episode of confusion (3.1) where they are **puzzling** and consulting the **notes**. After some work on the **whiteboard** with the **instructor**, they encounter another episode of confusion (3.2) where they are **puzzling** with **in class ideas** and providing **explanations**. They don't encounter any more episodes of confusion with the rest of the timeline showing a mix of **puzzling** and **building on ideas**.

From this analysis, we gain insight into how the coded themes change throughout time. For Groups 1 and 2, we see that some episodes of confusion are coded with both "Agree" and "Disagree" codes. This possibly indicates that confusion may arise from disagreement within the group and their shared idea of knowledge construction.

We can next focus on specific episodes to analyze more in depth as illustrated by episode 1.4.

Elaboration of Episode 1.4

As episode analysis will be used as the analysis moves forward, we elaborate on an episode of confusion where timelines illuminate a unique interaction during and after an interaction with an instructor. Group 1's discussion with a member of the instructional team included confusion at the beginning (1.2 & 1.3), and the end (1.4); the group got distracted and then returned to confusion (1.5). Below, we elaborate on episode 1.4.

During their interaction with a member of the instructional staff, Group 7 switched modes of reasoning from **puzzling** to **building on ideas** where the confusion seemed to subside (in between 1.3 and 1.4), shown in Fig. 4. The instructor asked the students to synthesize **in-class and out-of-class concepts** and asked them to **explain their reasoning**. In episode 1.4, the group spent most of the episode engaged in both **puzzling** and **building on ideas** and the confusion is centered around equilibrium. Near the end of episode 1.4, the instructor is present but does not talk and the group switches to exclusively being engaged in **puzzling.**

[00:18:41] Harris: We're talking about something at a reference… pressure, right?

[00:18:45] Beth: Reference is when it's at its pure state. But why are you using the reference?

[00:18:52] Harris: I'm just writing sh** down at this point. *((Harris chuckles))* Like, let's be so honest.

[00:18:58] Beth: I guess, Henry's originally is- So pure, super diluted. [Anna: So x_i basically. Maybe, okay, wait] maybe since this is just an infinite dilution, it's there.

[00:19:10] Anna: It's just right there… *((points at graph))* the tangent line like right there.

Harris asks the group a clarifying question to see if they were talking about something at reference pressure. Beth makes a connection to an **in-class** concept, stating that the reference just applies to when the species are in a "pure state." She then follows up her connection with a question to elicit an **explanation** from Harris, who with some roughness, notes how he's "just writing sh** down at this point." The roughness of his voice, the chuckle, and the sharpness of his words express **negative affect** and indicate confusion around the "reference pressure" concept. As this comes after a prolonged interaction with the instructor, his annoyance may come from the persistent involvement needed to solve the problem. Beth then connects the concept of infinite dilution to the selection of a specific point on the graph to which Anna responds by pointing out the tangent line on the **problem statement**. Instead of further engaging with Anna's interactions with the graph on the problem statement, the group begins talking about a TV show (after [00:19:10]), having the confusion result in an off-topic discussion.

Through the timeline we observed that students return to being confused near the end of and shortly after their interactions with the instructor. In future analysis, we hope to analyze episodes of confusion like the one shown above to understand the how the group's interactions and co-construction of knowledge may shift due to the instructor impacting the group's shared understanding.

Discussion and Implications

In this work, we use qualitative coding and timelines as a methodological tool to understand how students navigate confusion in a chemical engineering thermodynamics studio. Students worked in groups of 2-3 to solve a Henry's Law problem shown in Fig. 1. Through discourse analysis, we identified four themes: cohesion, reasoning, resources, and hedges.

Regarding our coding scheme, all four themes speak to aspects of co-constructing knowledge when making sense of challenging problems. Specifically, our themes are consistent with work in discourse analysis [10], sensemaking [40], [41], and sociocultural theories of learning [42] - [45]. Our method for determining episodes of confusion is consistent with others where we focused on finding instances where students explicitly expressed confusion as markers of incongruence in knowledge structures or, implicitly, through hedging and other tonal cues [1].

Our resources theme both contained material resources (e.g., consulting the internet, class notes, using the whiteboard, etc.) and interactions with a member of the instructional team. As co-construction of knowledge is embedded in context, the interactions students have with material tools and their instructors are important for considering how they leverage the environment around them to solve problems [46], [47]. Finally, our theme of cohesion is related to constructs in sensemaking that explore how students both construct and critique knowledge structures [40], [48] when figuring out how to solve problems. Agreeing and disagreeing can be seen as part of the critique done when sensemaking.

The richness of qualitative data can sometimes make it difficult to report as researchers wrestle with differences in interpretations, structuring coherent narratives, and trustworthiness. As we engaged with creating and analyzing the timelines, we observed how narratives of students negotiating through confusion was benefitted by a data visualization where time is the independent variable. This approach relates to work done by Atman et al. [49] to understand the differences of engineering design practices between novice and experienced engineers. Our future work will focus on reporting on the dynamics that emerge from the qualitative analysis. A benefit and possible limitation of timelines is that as they are visualization heavy, multiple design decisions must be made [11]. Although this variety gives researchers a multitude of ways to present their data, the decisions one makes may not always effectively convey the narrative of interest or may simply not be interpretable to the reader. Thus, we emphasize that timelines serve to supplement our overarching qualitative analyses. Authors 1, 2, and 3 discussed the coding scheme and design of timelines on multiple occasions to make design decisions that improved the timelines.

Another strength of the timeline is the ability to see how shifts in student reasoning and how those shifts co-occur with student-student and student-instructor interactions. As we mention above, Group 1 had an interaction with the instructor where **puzzling** shifted to **building on ideas** (between episodes 1.3 and 1.4) and quickly encountered another episode of confusion after the instructor leaves (episode 1.5). Confusion in episodes 1.4 and 1.5 were not around the same ideas as before, suggesting that interactions with instructors may play a role in scaffolding students' ability to engage in higher-order reasoning when the instructor isn't there [50]. We hope to study this in our future work through episode analysis of student-instructor interactions across our dataset, which contains 53 episodes of confusion.

As our aim with this work was to illustrate the use timelines as a research tool to study confusion, at this time we do not have conclusions on how this could influence instructional design and classroom management strategies for confusion. Additional contexts like those of a materials and energy balance course could be studied to observe how confusion manifests earlier in the chemical engineering curriculum.

Conclusion

In this work, we presented qualitative coding and timelines as a methodological tool to analyze how students navigate confusion in a chemical engineering thermodynamics studio. We used a discourse analytic approach to analyze video data of three groups of students solving a Henry's law problem and generated timelines for each group. We observed that timelines offered a productive way to scaffold a narrative around our complex dataset where students and instructors are constantly interacting. Timelines also help supplement the rigorous qualitative coding phase we conducted to understand different knowledge and social practices. In future work, we seek to further characterize the dynamics and relationships between cohesion, reasoning, resources, and hedges using episode analysis.

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APPENDIX A

Below we detail a possible solution path to the Henry’s law problem shown in Fig. 1.

Part a)

For species “a” in a binary mixture, the expression for the fugacity of a liquid is:

$$\hat{f}_a^l = \gamma_a x_a f_a^l$$

For an ideal solution, the activity coefficient (γ_a) will be 1, simplifying the expression to:

$$\hat{f}_a^l = x_a f_a^l(T,p)$$

The value of f_a^l will be constant at a given temperature (T) and pressure (p), thus, $\hat{f}_a^l$ increases linearly with respect to x_a shown as the **orange line** in Fig. A1.

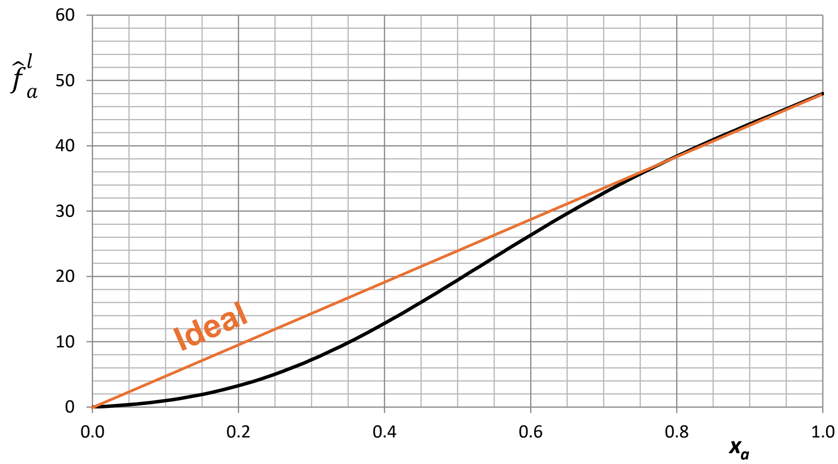

Fig. A1. Line that depicts the fugacity of species "a" in an ideal solution.

Part b)
Henry's law is derived for cases where there is an infinitesimally small amount of solute dissolved in a solvent. Thus, the Henry's law constant (H_a) is the limit of $\hat{f}_a^l / x_a$ as $x_a \rightarrow 0$. To find the value of H_a, a tangent to the plot of real solution behavior can be drawn as $x_a \rightarrow 0$ (shown as the **purple line** in Fig. A2.).

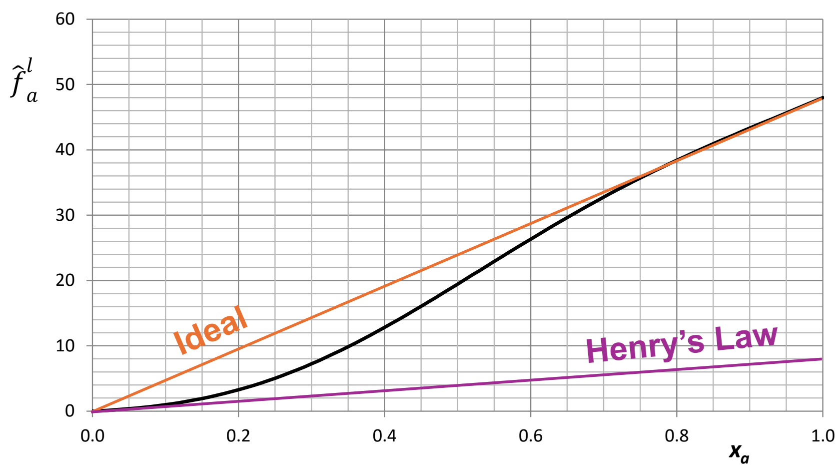

Fig. A2. Line that depicts Henry's law constant (H_a) as the limit of $\hat{f}_a^l / x_a$ as $x_a \rightarrow 0$.

Thus, we can take the Henry's law constant to be the following:

$$H_a = \Delta \hat{f}_a^l / \Delta x_a = (8\, bar - 0\, bar)/(1 - 0) = 8\, bar$$

Part c)
The activity coefficient is:

$$\gamma_i = \hat{f}_a^l / x_a f_a^0$$

$$\hat{f}_a^l (x_a = 0.4) = 13\, bar$$

The pure species fugacity for species "a" can be found by finding the value $\hat{f}_a^l$ at $x_a = 1$.

$$f_a^0 = 48\, bar$$

Plugging in all the numbers in yields:

$$\gamma_a = (13\, bar)/(0.4)(48\, bar) = 0.68$$

Part d)

Unlike interactions dominate as the $\hat{f}^{l}_{a,real} < \hat{f}^{l}_{a,ideal}$ from x_a in the range of 0 – 0.7. In other words, species "a" has attractive interactions with species "b", decreasing the amount of species "a" in the vapor phase.