2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
ASEE
Paper ID #39480

Teaching Fugacity through Comics and Assessing the Impact on Student Confidence and Understanding

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Abstract

Comics have been used as learning tools in engineering education for several years with positive feedback from students and educators. The comics have been developed by integrating written lectures and instruction with visual depictions to provide new curricula to help students better grasp more abstract and complex topics, effectively providing students with 'visual notes' that allow them to revisit the lectures where the concepts were originally taught and helping them to form deeper connections with the subject matter. In a number of general studies, integrating the comics into instruction or simply providing them as additional tools have been determined to increase the students' interest, confidence, and understanding of the concepts addressed.

One particular 10-page comic, developed in collaboration with a professional artist, focused on the subject of fugacity. This comic has since been used by a number of educational institutions, as well as international federal agencies and even as supporting evidence in a legal case to help explain the concept to a jury. It has clearly been received well given its broad adoption; however, the impact of the comic has never been truly assessed in a formal educational setting. In order to evaluate the comic, students in two thermodynamics sections were provided the comic at the end of their fugacity instruction. Students were provided a series of ConcepTest questions focused on important features of fugacity in gases, liquids, and mixtures, in order to best measure their understanding. Following each question, students were asked to assess their confidence in the answer they provided. Students then read through the comic, before answering the ConcepTest questions again and providing another assessment of their confidence. Differences in their answers and self-assessment were then evaluated to determine the effectiveness of the comic.

This paper discusses analysis of the comic with consideration of how to integrate a comic learning tool into thermodynamics courses for greatest positive impact.

Background

Comics have been a long history of being an effective visual learning tool, with potential application to nearly all fields of study. Comics have been known to have a positive impact as educational tools since the 1940s, with a significant number of studies investigating their use in K-12 classrooms and entire issues of peer-reviewed journals being devoted to this efforts.[1-6] After social backlash in the 1950s negatively impacted the reputation of comics and ended most of the research being conducted on comics in education,[7-8] despite the majority of studies at the time indicating their broad positive potential, comics only began to be reintroduced in formal learning environments in the United States over the past two decades.[9-13] Now, educational comics are readily being produced to cover a range of fields, particularly in STEM at all levels of learning, with positive impact having been shown in covering topics of medical techniques,[14-15] solar-terrestrial phenomena such as global warming and geomagnetism,[11] biology,[16-17] anatomy,[18] polymer science,[19] and mathematics.[20] Overall, comics continue to show great potential as educational tools, even as the majority of current efforts appear to be focused on creating and developing these tools as compared to analyzing their impact.

The potential for comics as educational tools in engineering is particularly interesting, given that previous studies have established engineering students have a general preference for visual learning tools.[21-23] While much of STEM instruction can cover difficult theoretical and mathematical concepts that do not have an obvious visual component, comics provide a means of combining the necessary text and equations with visual media to provide a visual connection for the concepts addressed.[24] These comics can be developed

to further facilitate student engagement and learning, depending on the structure of the instruction. For example, the comics could incorporate a dialogue between characters, with one character serving as the student stand-in and asking questions that students would typically ask while learning the subject matter. The comics can present the concepts through a full narrative with relevant real-world context, allowing for greater connection to be established between the concepts and application. The comics can also utilize captions integrated into graphic art to depict scenes that would be difficult to present in a standard classroom. Finally, the comics themselves can be directly incorporated into a student's class notes in print or digital form, and capture and depict a lecture they had previously received, allowing for visual connections that can be readily reviewed in informal settings for reinforcement of their understanding.

The authors had previously developed a series of comics for use in chemical engineering courses at the undergraduate level and evaluated their initial impact on student interest, confidence, and understanding.[25-26] These comics included discussion of purge and recycle streams,[27] the first law of thermodynamics,[28] assumptions,[29] heat exchangers,[30] and other chemical engineering concepts. In general, the comics were shown to have a significant effect on students' self-reported interest in the subject matter and confidence in being able to address problems or applications involving the concepts that the comics addressed.[25-26] The impact of understanding was less clear, depending on how the comics were implemented. Small improvement was observed in student performance on exams and lab reports for some courses, while other results were mixed if the instructor was not directly supportive of the comics being introduced. In some cases when comics developed by students were incorporated into the supplied reading, such as for a heat and mass transfer course, exam averages increased by nearly 20 points.[31] From these initial studies, the potential for positive impact on student engagement and comprehension from the integration of the comics into their educational experience was clearly demonstrated.

From these previously developed comics, the comic that became the most popular, and received the greatest number of requests from other institutions to be used in their instruction, was the ten-page comic focused on fugacity.[32] Over sixty other colleges both nationwide and internationally integrated the fugacity comic into their instruction, and several companies requested to use it as part of their orientation training for new employees. Additional requests to use the comic included representatives of the Ministry of Environment and Food of Denmark and their Environmental Protection Agency, as well as a lawyer representing the City of Phoenix that needed to explain fugacity to a jury in a court case. The comic also was linked and shared in other resources, including being the focus of a popular post shared between students on the Chemical Engineering subreddit.[33] Pages from this comic are depicted in Figure 1.

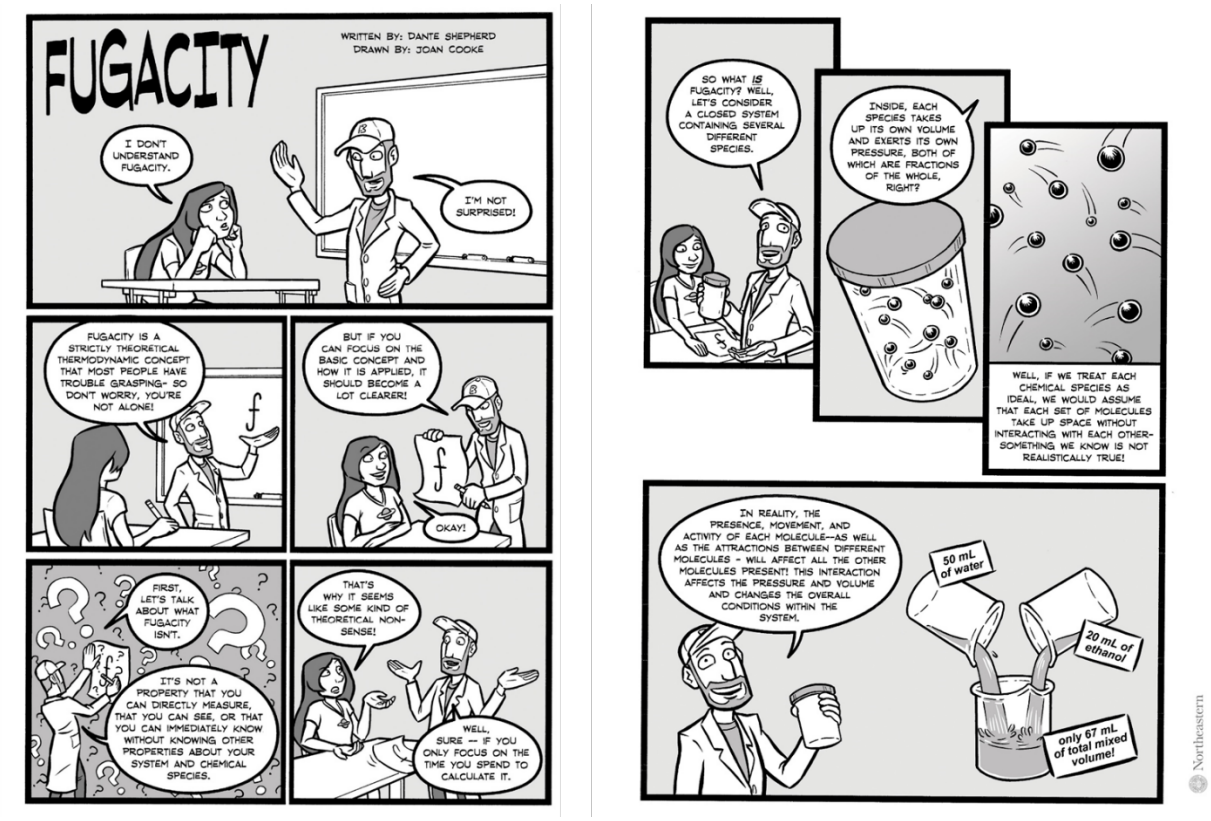

Figure 1. Pages 1 and 2 of 10 from the "Fugacity" comic.[32]

In general, both instructors and users were enthusiastic about the fugacity comic learning tool. However, this comic was the one that had been least evaluated in terms of its impact on student interest, confidence, and understanding. The fugacity comics had been studied for impact once through student surveys and a series of ConcepTest questions.[26] A clear positive impact on students' self-reported interest and confidence could be observed through students' answers on the surveys via a 4-point Likert scale, with over 85 percent of students reported increased confidence in fugacity concepts and nearly 95 percent of students encouraging the comics to be used with instruction in future classes. These results are presented in Figure 2. However, this study had been conducted through an instructor who had been openly skeptical of the comics' potential to the students, which led to the perception that the evaluation of the students' understanding may have been adversely affected by the instructor's presentation of the comics. Evaluation of the understanding was conducted by having students answer 10 multiple choice ConcepTest questions designed to assess conceptual comprehension of fugacity after the classroom instruction on fugacity had been completed, then providing them the fugacity comic to review overnight, before having the students answer the same 10 ConcepTest questions the following day. Results from student answers provided no clear insight into any impact on understanding, as presented in Figure 3. Given the biased presentation of the comic, compared to the enthusiastic response by not only students but other educators using the comic in courses at other institutions, further analysis was necessary to determine if any impact on understanding could be observed.

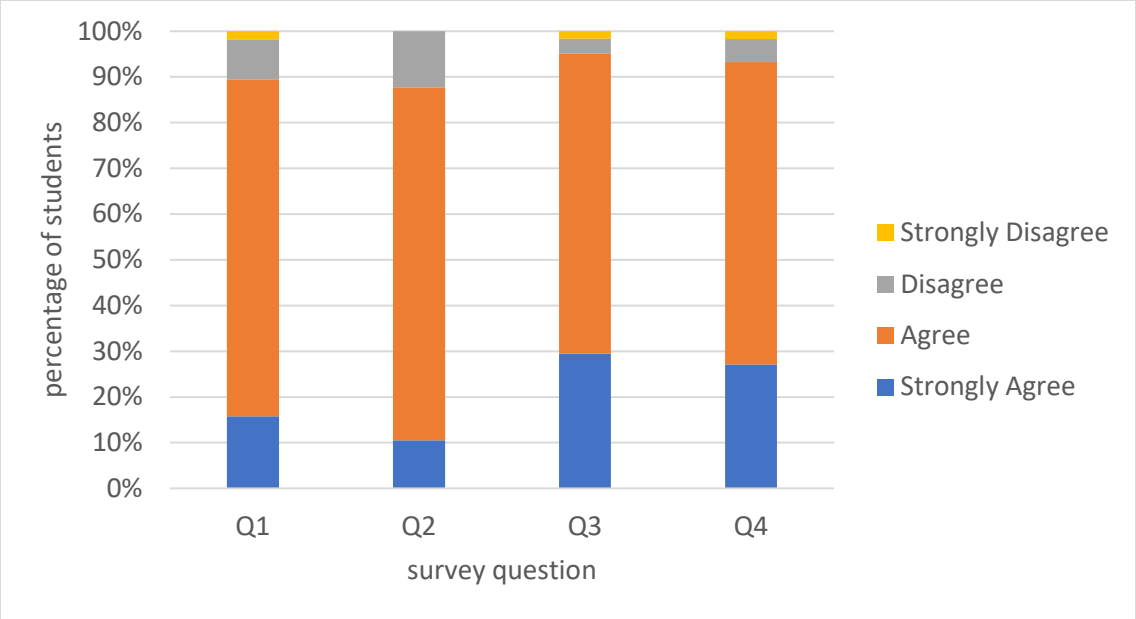

Figure 2. Responses from student surveys on self-reported interest and confidence in the previous evaluation of the fugacity comic. Q1 = "Was this comic helpful to your understanding?" Q2 = "Do you feel more confident in your understanding?" Q3 = "Would you recommend this comic to other students?" Q4 = "Do you like comics?"

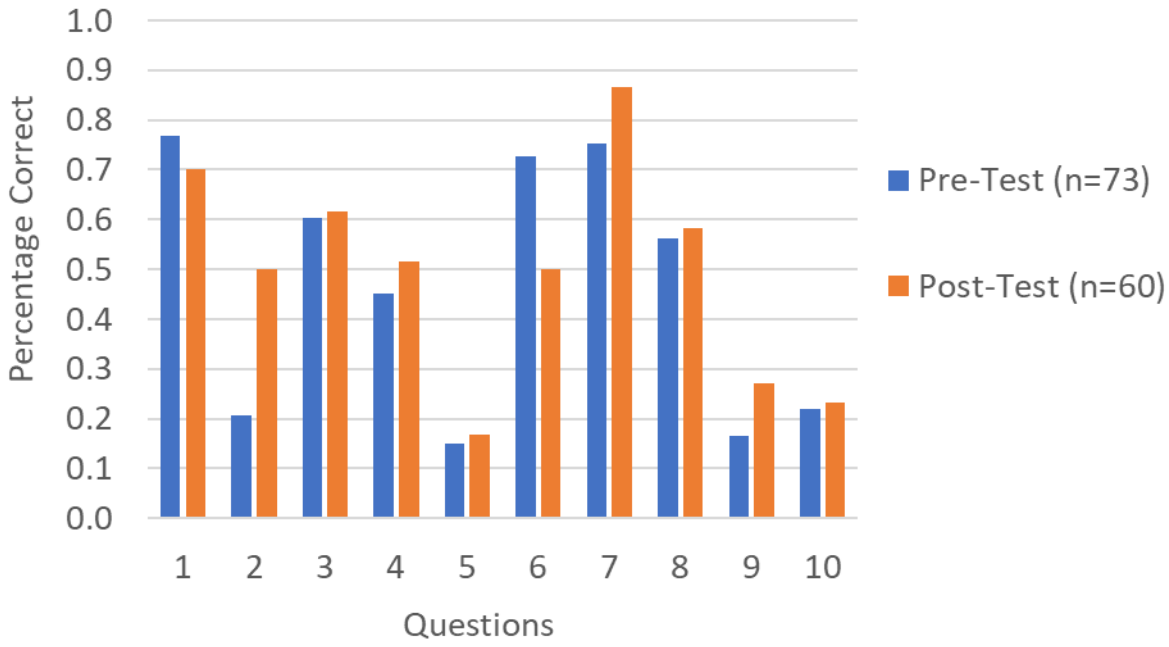

Figure 3. Percentage of correct answers on each ConcepTest question provided to students, both before and after reading the fugacity comic.

Methods

Instructors at Northeastern University have been using the fugacity comic in their thermodynamic courses for several years, so students are aware that they will be provided the comic at some point in the course. As such, it is difficult to compare to a control group that has not received the comic; earlier sections that took the course before the comic was created occurred long enough ago that other curriculum changes have occurred that would have a greater influence on any observed learning impact, and withholding the comic from one section of students would not be possible as the learning tool would be shared with them by the other section before any analysis could be completed. As such, evaluation of student learning within Northeastern University would need to be conducted comparing student's interest, confidence, and understanding from before engaging with the comic to after reading the comic.

In two sections of Thermodynamics II course, which at Northeastern University focuses on chemical equilibrium and is where fugacity is first introduced, students were provided a link to an online survey to be taken outside of class time, at a point in the semester in which the majority of their instruction on fugacity had been completed but before applications of fugacity in vapor-liquid equilibrium and other mixtures had been fully introduced. Of the 41 students across the two sections, 32 participated fully in the survey. Students were first asked to evaluate on a 1-4 point Likert scale regarding the instruction they had received to date and their confidence in the subject matter. Students were then given a series of 10 ConcepTest questions taken from LearnChemE.com that directly focused on different aspects of fugacity. These questions could be grouped into four categories: 1) existing systems with multiple phases present, 2) an existing single system with a new component being introduced to it, 3) two existing systems mixing together, and 4) mass transport of components when two separate systems were connected to each other. As part of answering each multiple choice questions, students were tasked with evaluating their confidence in their answer on a 1-4 point Likert scale, with 1 representing "unconfident", 2 representing "somewhat unconfident", 3 representing "somewhat confident", and 4 representing "confident". Students then read the 10-page fugacity comic, before being asked to reevaluate their confidence and understanding. Following this self-assessment, students answered the same 10 ConcepTest questions and evaluated their confidence in each answer again. Finally, students were asked if they felt the comic helped improve their understanding of the subject matter, if the comic was helpful, and if they would recommend comics to others for their educational use.

From the self-assessment questions, 97 percent of the students either agreed or strongly agreed that the comic was helpful and 90 percent felt that the comic specifically helped improve their understanding of fugacity. All students agreed or strongly agreed in recommending the comic for other students to use in their learning. These results are presented in Figure 4. The survey answers also revealed improvement for the group as a whole on their confidence in being able to solve problems related to fugacity. Prior to reading the comic, 37 percent of the students reported feeling either unconfident of somewhat unconfident with fugacity; after reading the comic, this was reduced to 6 percent of the students, as presented in Figure 5. Overall, 53 percent of students reported the same level of confidence, and 44 percent of students reported an improvement in confidence; interestingly, only one student reported a decrease in confidence, but explained that the comic actually helped them realize the full complexity of fugacity and that they had previously been overconfident in their understanding. These initial qualitative results indicated that the fugacity comic did indeed have a positive impact on student engagement and confidence as was previously assumed.

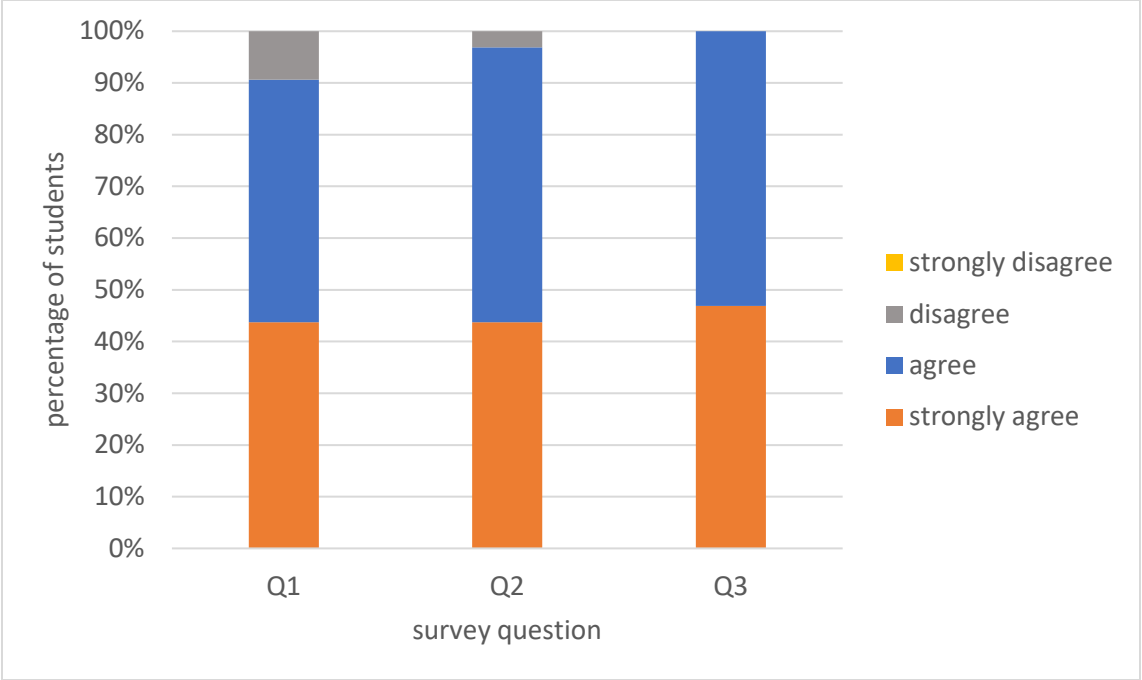

Figure 4. Self-assessment from students (n=32) after reading the comic. Q1 = "Do you feel the comic helped improve your understanding of the subject matter?" Q2 = "Do you feel that this comic was helpful?" Q3 = "Would you recommend science comics like this to others as a means of learning?"

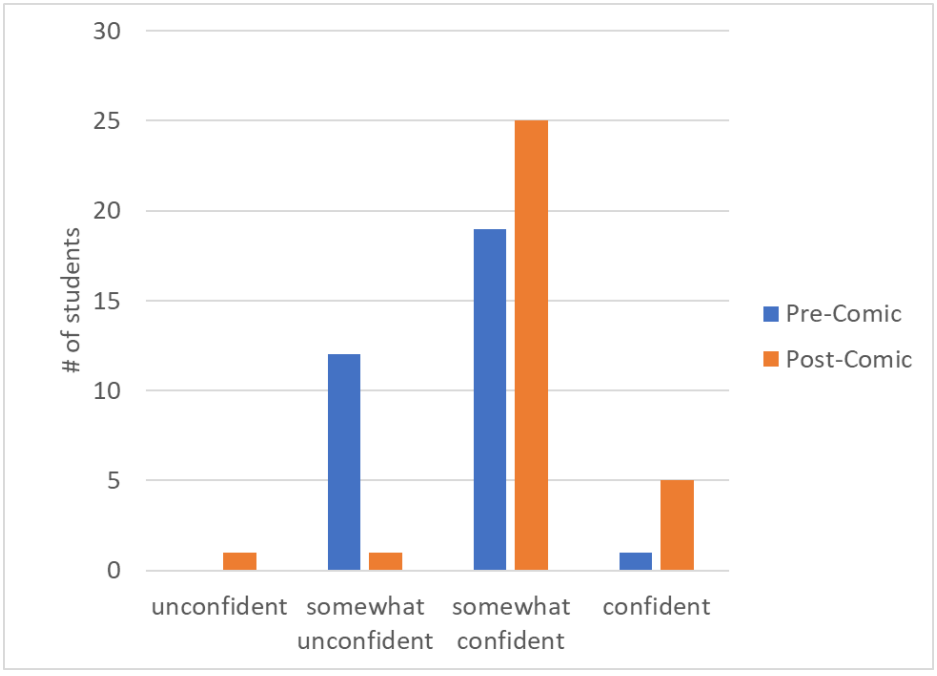

Figure 5. Number of students (n=32) reporting degree of confidence in fugacity both before and after reading the comic.

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Comparison of student answers for the ConcepTest questions was far less indicative of clear improvement in student understanding. In answering the questions, students could essentially fall into five categories: if they changed their answer from pre-comic to post-comic, they could either a) change from being incorrect to correct, b) change from correct to incorrect, or c) change from being incorrect to another incorrect answer; if they held their answer the same, they could either d) remain correct or e) remain incorrect.

Students changed their answer on the ConcepTest questions 35.9 percent of the time, with only 12.5 percent of students changing from an incorrect answer to the correct option. Of the 64.1 percent of the time that students held their answer the same, 30.3 percent of the time the answer remained correct. Overall, student answers improved from being correct 36.9 percent of the time to 42.8 percent of the time. These overall data are presented in Table 1.

Table 1. Overall student responses on the ConcepTest questions from pre-comic to post-comic.

Changed Answer	35.9%	Incorrect -> Correct	12.5%
		Correct -> Incorrect	6.3%
		Incorrect -> Incorrect	17.2%
Held Answer	64.1%	Correct -> Correct	30.3%
		Incorrect -> Incorrect	33.8%

Student strength with different aspects of fugacity varied. Students demonstrated the highest understanding of fugacity on ConcepTest questions describing a single system with multiple phases. On the three ConcepTest questions addressing problems with this scenario 54.2 percent of student answers were correct pre-comic and remained correct post-comic. Student overall answers only slightly improved from being 63.6 to 65.7 correct, as presented in Table 2.

Table 2. Student responses on ConcepTest questions addressing fugacity in a single system with multiple phases, from pre-comic to post-comic.

Changed Answer	27.1%	Incorrect -> Correct	11.5%
		Correct -> Incorrect	9.4%
		Incorrect -> Incorrect	6.3%
Held Answer	72.9%	Correct -> Correct	54.2%
		Incorrect -> Incorrect	18.8%

For ConcepTest questions addressing fugacity in the flow of two separate systems that are connected to each other, a scenario specifically depicted in the comic through an example on one page, students showed the largest improvement in their answers, going from 19.8 percent correct pre-comic to 32.3 percent correct post-comic. These data are shown in Table 3.

Table 3. Student responses on ConcepTest questions addressing fugacity for flow of two systems connected together, from pre-comic to post-comic.

Changed Answer	46.9%	Incorrect -> Correct	17.7%
		Correct -> Incorrect	5.2%
		Incorrect -> Incorrect	24.0%
Held Answer	53.1%	Correct -> Correct	14.6%
		Incorrect -> Incorrect	38.5%

For the two ConcepTest questions with a similar focus, addressing fugacity of two separate systems that mix together into a single system, student answers improved from 34.4 percent correct pre-comic to 42.2 percent correct post-comic, as indicated in Table 4.

Table 4. Student responses on ConcepTest questions addressing fugacity of two systems mixing together into a single system, from pre-comic to post-comic.

Changed Answer	31.3%	Incorrect -> Correct	12.5%
		Correct -> Incorrect	4.7%
		Incorrect -> Incorrect	14.1%
Held Answer	68.8%	Correct -> Correct	29.7%
		Incorrect -> Incorrect	39.1%

Finally, for the two ConcepTest questions addressing fugacity in a single system after a new component is added to the mixture, students had the smallest improvement with the lowest measurement of understanding, improving from 23.5 correct pre-comic to 25.1 correct post comic, as indicated in Table 5.

Table 5. Student responses on ConcepTest questions addressing fugacity of a system with a new component added, from pre-comic to post-comic.

Changed Answer	37.5%	Incorrect -> Correct	6.3%
		Correct -> Incorrect	4.7%
		Incorrect -> Incorrect	26.6%
Held Answer	62.5%	Correct -> Correct	18.8%
		Incorrect -> Incorrect	43.8%

It is worth considering that students also reported their confidence in each answer both pre- and post-comic on a 1-4 Likert scale. In all cases, average student confidence increased with the second time they answered the ConcepTest questions as presented in Table 6, which would again reflect the general self-reported improvement in confidence as measured in the additional survey questions. The greatest confidence both pre- and post-comic were expressed by students who answered correctly pre-comic and then stayed with their same correct answer. The lowest confidence were expressed by students who were incorrect pre-comic and changed their answer to another incorrect option.

Table 6. Average student reported confidence in their ConcepTest answers from pre-comic to post-comic, for each combination of potential answers.

	1st Time Answering	2nd Time Answering
Incorrect -> Correct	2.2	2.9
Correct -> Incorrect	2.3	2.9
Incorrect -> Incorrect	2.1	2.4
Correct -> Correct	2.7	3.3
Incorrect -> Incorrect	2.5	2.9

Student feedback also helped to provide further insight into the impact of the comic. In most cases, students expressed positive engagement with the comic:

- "Fugacity is difficult to understand and calculate, but it makes me enjoy learning when I know that the professors are willing to go the extra mile for us to understand the concept. Thank you."

- "I really enjoyed the comics, and most concepts became much more clear after that. The example problems you put on the comics where incredibly useful."

- "I think comics incorporated throughout lectures would be super fun and cool!"

Students that did not find the comic to be helpful reflected that their preferred visual learning tools were a different medium than comics:

- "I think that the comic is extremely informative and fun to read! I've just never been a book or comic reader because I like to learn things through watching videos."

Students also reflected that the comic helped provide context for fugacity, which in itself was helpful, but could be a challenge if the formal learning instruction did not effectively provide the same context:

- "Before taking this survey I thought I had a decent grasp on fugacity. I still think my understanding of the equations is solid, but I realize now that we haven't discussed the intuition or context for fugacity at all, which is a problem I find to be common among multiple topics in multiple chemical engineering classes."

The last reflection point brings to question the impact that a comic can have when used as an informal supplemental learning tool to a formal learning environment; if the learning tool does not align with the instruction, it may effectively be a disjointed learning experience and be counterproductive. Thus even the comic is perceived well, it may not have a positive impact overall.

Conclusions

From a more thorough investigation of the fugacity comic, the comic was indicated to be a good supplemental tool to help with reader engagement on the concept and broader context associated with fugacity. There is a clear improvement in student interest and confidence in the subject matter based on student self-assessment, which is an important factor to ensure that students are engaging with the concepts and willing to try to apply concepts for potentially challenging problems. The impact on student understanding is mixed, and may be reflective of both the difficulty of the topic as well as how the comic itself can only provide part of the overall instruction on the concepts. Depending on how the comic is integrated into the instruction, the increased student interest and confidence may allow the instructor to better reinforce instruction and facilitate deeper understanding for students who find a learning tool like this useful.

Given the broad use of this comic at multiple institutions, it would be worth continuing to investigate the comic's impact with students of different backgrounds to better determine how comics can be most optimally implemented into course materials. More specifically investigate any correlation between a student's preference for visual learning tools and any improvement in their interest, confidence, or understanding. Further studies will seek to continue this work in conjunction with other comics developed by the research team to help provide best suggestions for other instructors on how these tools can be used to support their students and supplement their instruction.

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*-Shepherd, D. is the pseudonym of the author, Lucas Landherr.