2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #53110

Integrating an AI-Driven Socratic Tutor into Process Control Education

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Abstract

Chemical engineering courses in process control and process design challenge students to integrate mathematical modeling, systems thinking, and open-ended problem solving. However, students often struggle to make the cognitive connections between theory and application, particularly in reasoning through complex, multivariable problems. In this paper, we present the design and implementation of an AI-based Socratic tutor created to promote deeper learning in an undergraduate chemical engineering course through structured questioning and reflection. The AI tutor interacts with students solely through questions, prompting them to articulate reasoning, justify decisions, and confront misconceptions—mirroring the inquiry-based dialogue characteristic of effective one-on-one tutoring.

Grounded in principles from cognitive science that support student acquisition of knowledge and skills using active learning, the Socratic tutor was deployed in one senior-level course: *Process Dynamics and Control* and planned for later deployment in other chemical engineering courses within the undergraduate curriculum. The AI agent was trained with a curated primary knowledge base assembled by the course instructor, consisting of publicly available textbooks, technical references, and web resources verified to be accurate and appropriate for the course content. This knowledge base supported alignment between the tutor's questioning, course objectives, and chemical engineering best practices. Students engaged with the tutor periodically throughout the semester on topics related to the current course delivery. Following their interactions, students completed surveys reflecting on their experience and evaluating their perceived learning. The results of the perceived learning survey were compared with data from prior course offerings that did not use the Socratic tutor to determine changes in self-reported understanding, confidence, and engagement.

Preliminary findings indicate that students perceived the AI tutor as an effective tool for reinforcing conceptual understanding and promoting self-directed learning. Students reported that the question-based format encouraged them to think more critically before seeking answers and to explain their reasoning more clearly. This paper describes the development of the curated knowledge base and AI Socratic tutor, presents comparative survey results, and discusses implications for integrating AI-driven metacognitive tools into chemical engineering curricula to strengthen conceptual mastery and student independence in learning.

Introduction and Background

Senior-level chemical engineering courses, specifically 'Process Control' and 'Process Design, present a unique pedagogical challenge. These courses require students to integrate mathematical modeling and systems thinking to solve open-ended, multivariable problems [1]. However, a persistent gap exists in the transition from coursework to practice; students often struggle to make the necessary cognitive connections between theoretical principles and practical application.

In traditional lecture environments, when faced with these complex abstract reasoning tasks, students often default to seeking immediate answers rather than engaging in the "productive struggle" required for durable learning [2]. This reliance on correct answers can bypass the development of engineering judgment, which requires justifying decisions and confronting misconceptions.

The rapid integration of artificial intelligence (AI) tools in engineering education has introduced significant tension. While AI offers powerful support for learning, it simultaneously presents a risk of "cognitive offloading," where students reduce their mental effort by relying on the tool to perform the cognitive processing [3], [4]. If used passively, AI tools can exacerbate the student's tendency to bypass reasoning processes. However, this technology also offers a unique opportunity to address personalized instruction. By constraining the AI's interaction, we can leverage these tools not to provide answers, but to facilitate inquiry. We propose that Socratic questioning with structured and challenging dialogue offers a method to utilize AI's capability without undermining the cognitive work required of the student [5].

The efficacy of a question-based AI tutor is grounded in well-established principles from cognitive science that support active learning. Specifically, the Socratic approach activates three critical mechanisms: (1) retrieval, (2) elaboration, and (3) metacognitive monitoring. By asking students to recall and apply relevant theories without prompts, the tutor strengthens long-term memory access. Research demonstrates that this act of retrieval produces greater learning gains than repeated study or elaboration alone [6], [7]. The tutor prompts students to articulate their reasoning and justify their decisions. This act of elaboration forces the learner to connect new knowledge with existing mental models [8]. By constantly assessing the validity of a student's logic, the system encourages students to monitor their own understanding and to identify gaps in their knowledge before moving forward. This is the basis of metacognition [9], [10].

While AI tutoring systems are becoming common, the majority focus on explanation delivery or direct answer generation. There is a distinct lack of reported implementations of AI tutors in chemical engineering that are strictly constrained to question-only interactions. Most existing tools prioritize "helpfulness" (providing the solution) over "pedagogical scaffolding" (guiding the learner to the solution) [11]. To address this gap, this paper presents the design and deployment of an AI-based Socratic tutor created to promote deeper learning in senior-level undergraduate chemical engineering courses. Unlike general-purpose chatbots, this agent was trained with a curated primary knowledge base assembled by instructors, consisting of verified textbooks and technical references to ensure accuracy and alignment with course learning outcomes.

Socratic Tutor Design and Course Integration

The AI Socratic Tutor was designed to support the educational needs of students in Process Design and Control. The intent of its implementation was to encourage and enhance student reasoning about the course content, without directly providing answers. By designing the agent to act in this manner, students make connections between concepts and solidify their understanding by having to explain their reasoning to the AI Socratic Tutor. This section will describe how this was accomplished and how the AI Socratic Tutor was integrated into the course.

AI agents and their behavior can be shaped by the instructions given to the agent within the configuration of the agent. The AI Socratic Tutor was created within the Microsoft Copilot Large Language Model. Copilot was chosen because of the enterprise license held by our university, with the assurance that Copilot would not save any prompts or answers nor use any of these to train its model. The AI Socratic Tutor behavior was constrained during configuration to do the following:

1. It would only ask students questions in a Socratic-like dialog,
2. It would use as primary sources a curated set of materials, and
3. It would confine the discussions to topics appropriate to an undergraduate level of process control.

The configuration prompt and intended primary website sources are provided in Appendix A. The configuration prompt is intended to shape the behavior of the agent to follow up on a student-supplied topic by asking clarifying questions, asking students to state or justify their assumptions, and encouraging them to reflect on their own thinking. The curated list of websites, including the text used in the course, made freely available on the web by the author and copyright holder, Thomas E. Marlin[12].

Written reflections that accompany each homework set and ask students to write about their thought process as they solve homework problems have long been used in this course. These written reflections ask students to identify the concepts they used to solve problems, the limitations or assumptions of the method they used, and how these concepts fit into the scope of the topics in the course. The written reflection assignment is provided in Appendix B. The AI Socratic Tutor was introduced in Fall Semester of 2025 as an alternative to these written reflections. The written reflection was retained as an option for students who preferred not to use AI or objected to the use of AI. Students who chose to use the AI Socratic Tutor to earn the "reflection" portion of their homework points were asked to interact with the agent for 20 minutes on a topic covered by the current homework problem set and to upload a transcript of their interaction. As an attempt to reinforce the Socratic questioning behavior of the agent, students were asked to begin each session with a prompt of the format:

> *"I'd like to explore [insert chosen topic]. Please ask only questions to guide this discussion as a Socratic tutor would."*

Appendix C contains the full assignment document provided to students for the AI Socratic Tutor usage.

Survey Methodology and Administration

Students were surveyed at the conclusion of the semester to examine their perceptions of learning and engagement during the course and concurrent process control laboratory course. The survey instrument was adapted from prior work by Firth et al. [13] and modified to reflect the gains from learning activities in the Process Dynamics and Control course, in addition to learning gains from the associated laboratory course. Of the 54 students registered in the course, 24 students responded to the survey.

Survey items asked students to rate their perceived learning gains using a five-point Likert scale (1 = no gain, 2 = a little gain, 3 = moderate gain, 4 = good gain, 5 = great gain, with an option for not applicable). Questions were grouped to examine perceived gains in three areas: (1) conceptual understanding of course-specific chemical engineering topics, (2) application of concepts to open-ended problems, and (3) attitudes and behaviors related to learning, including reflection, confidence, and self-directed reasoning. Students were asked to rate their learning gains in each of the 3 area groups considering their experience in the Process Dynamics and Control course and again considering their experience in the concurrent controls lab course. The survey questions are listed in Appendix D. Survey results from the ratings regarding the theory course were compared between groups of students who reported primarily using the AI Socratic Tutor and those who reported primarily using the written reflection option. Survey results from the ratings regarding the experience in the lab course were compared to responses from prior course offerings in which the Socratic tutor was not used in order to examine changes in student perceptions associated with the introduction of the AI-based learning tool. As with all self-reported measures, these results reflect student perceptions rather than direct assessments of learning outcomes and should be interpreted accordingly.

Student Usage and Perceptions

Student adoption of the AI Socratic Tutor option progressed from 50% of submissions on Homework 1 to an average of 80% of submissions for the remainder of the assignments. The distribution of submissions between the two options is shown in Figure 1. Approximately 12% of students were consistent in their choice of the written reflection option and never tried the AI Socratic Tutor. Another 42% of students only utilized the AI Socratic Tutor. The remainder experimented with both to some extent. Figure 2 shows the distribution of students based on the percentage of submitted reflection assignments they chose to use the AI Socratic Tutor.

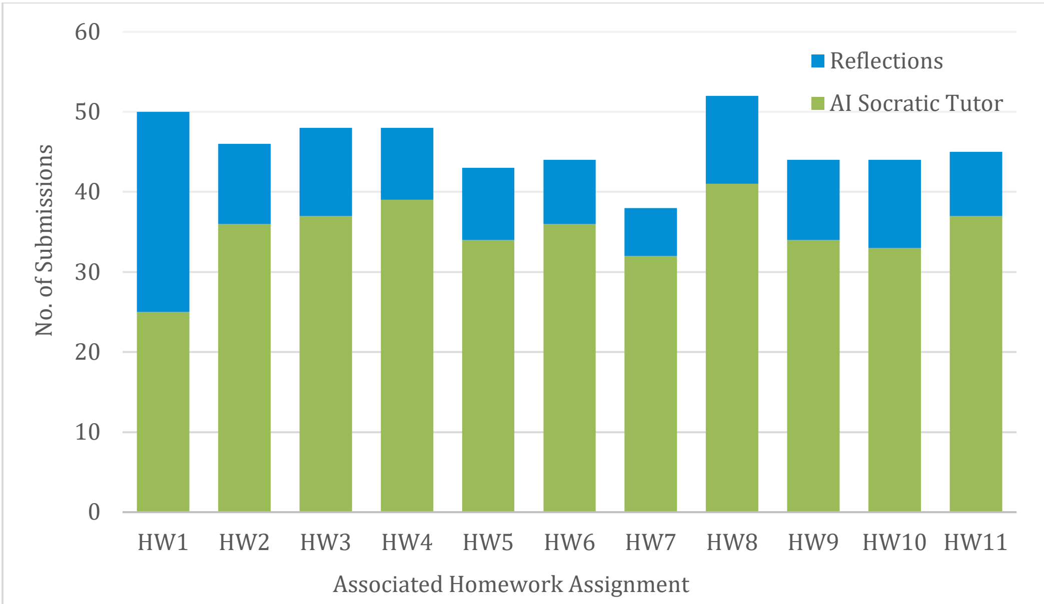

Figure 1: Distribution of submissions between the original written reflection assignment and the new AI Socratic Tutor option

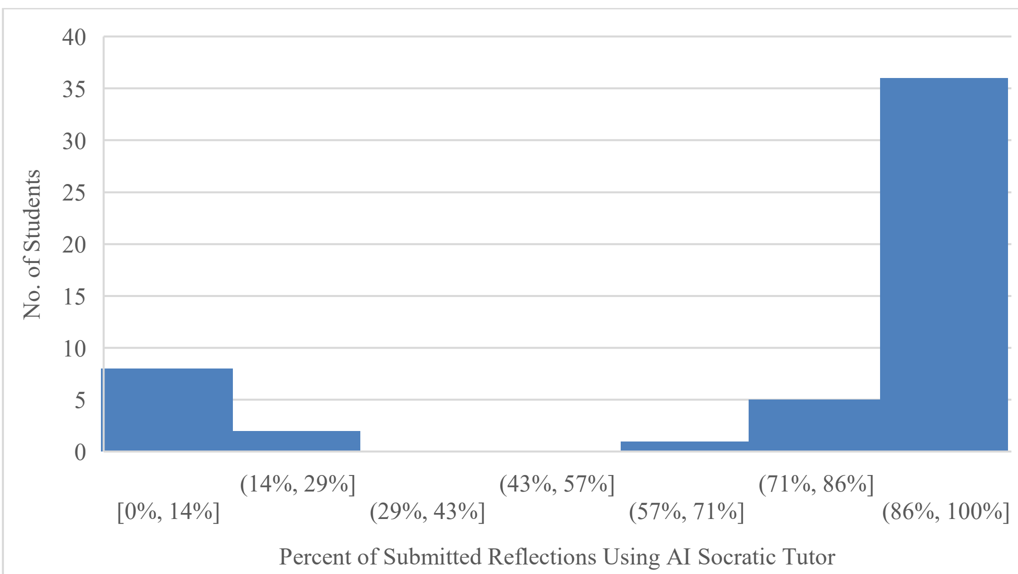

Figure 2: Distribution of student use of the AI Socratic Tutor option for homework reflection assignments

Students who utilized the AI Socratic Tutor primarily did so using the designed Copilot agent. However, one student used their own LLM account that did not have the Socratic tutor behavior, and thus it provided answers rather than guiding the discussion via questioning. In addition to the possibility that students could use another LLM and submit that directly, there exists the possibility that students could use another LLM to answer the AI Socratic Tutor's questions. One other possibility exists that a student could jailbreak the AI Socratic Tutor and instruct it to disregard prior instructions to ask questions, and to now only provide answers. This conduct cannot be prevented but can be limited by careful reading of the student submissions to determine proper usage and credit to be awarded. Neither of the latter two possibilities were observed in this cohort of students. In addition, there did not appear to be any misleading or incorrect responses from the AI Socratic Tutor, as assessed by the instructor and grading TA.

The vast majority of students using the AI Socratic Tutor engaged in good faith with the agent. Anecdotal reports from the students indicate that it was valued by them as a positive experience that added to their learning. A few students reported engaging with the agent for well beyond the requested 20 minutes, up to as much as 45 minutes. One complaint was that the questioning behavior got "annoying", because the agent wouldn't stop asking questions.

Survey Results and Interpretation

As stated earlier, of the 54 students enrolled in the Process Dynamics and Control course, 24 students responded to the survey on self-perceived learning gains. Each student gave consent to be surveyed and was assured that their responses were anonymous and that completion of the survey was strictly voluntary. The information provided to students at the beginning of the survey is shown in Appendix D. Students identified on a Likert scale from 1 to 5 how often they used the AI Socratic Tutor for their reflection assignments, where 5 represented 100% of the time and 1 represented 0% of the time. Based on this self report, respondents were divided into 2 groups based on their AI usage: Majority AI users (those with a rating of ≥ 4 on the Likert scale) and Minority AI users (those with a rating of ≤ 3 on the Likert scale). The Majority AI users group contained 19 respondents and the Minority AI users contained 5 respondents. We selected a threshold of ≥ 4 to operationalize "majority use" because, on a 1–5 frequency scale anchored at 1 = 0% and 5 = 100%, responses of 4-5 represent use on most or all reflection assignments, whereas 1-3 represents infrequent-to-moderate use (approximately half or less). Given the small sample, we used this high/low-frequency collapse to support interpretable descriptive comparisons while avoiding very small cells across five response levels. Because of the low number of survey respondents and the further division of respondents based on the grouping, there is not enough statistical power to infer any causal effect from the AI Socratic Tutor use. However, there are associations that may prove interesting and could inform further research.

Figure 3 shows the survey items that had a statistically significant difference in median using a Wilcoxon Rank Sum test with $\alpha = 0.1$. In this box plot, the median is indicated by the red line. The survey item number and a short question description is indicated on the horizontal axis. This number corresponds to the question numbers and full questions listed in Appendix C. In addition C_noAI indicates the data pertaining to the Minority AI user group as they were asked to consider the theory course and the C_AI indicates data from the Majority AI user group with the same prompt to consider the theory course. Directionally, there are higher perceived learning gains among the Majority AI users.

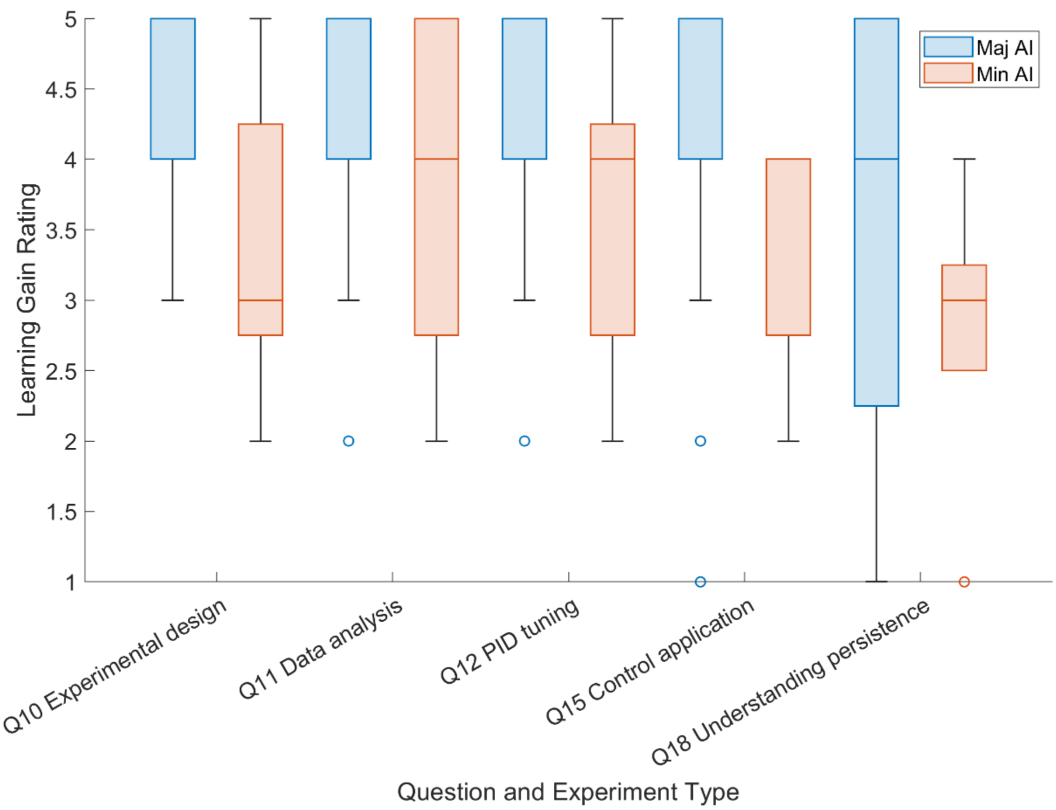

Figure 3: Perceived learning gains of Minority AI users and Majority AI users in the 2025 cohort when considering learning from the Process Dynamics and Control course

Those who reported their use of the AI Socratic Tutor for the majority of their reflections rated their learning gains higher than did the Minority AI user group on their: ability to design a control experiment, analyze data to determine model constants, tune a PID controller, and persistence in the pursuit of concept understanding. However, this could be due to the type of student who would elect to use AI, and not due to the use of AI itself.

The 2025 cohort was also asked to rate their learning gains considering their experience with the unit operations equipment and experiments in the Controls Lab course. These perceived learning gains were compared to the responses of a cohort in 2024. The Majority AI user group in 2025 was compared to the 2024 cohort on these items to assess difference between AI Socratic Tutor use and no formalized course exposure to AI as a learning tool. Figure 4 shows the survey items that had a statistically significant difference in median using a Wilcoxon Rank Sum test with $\alpha = 0.1$.

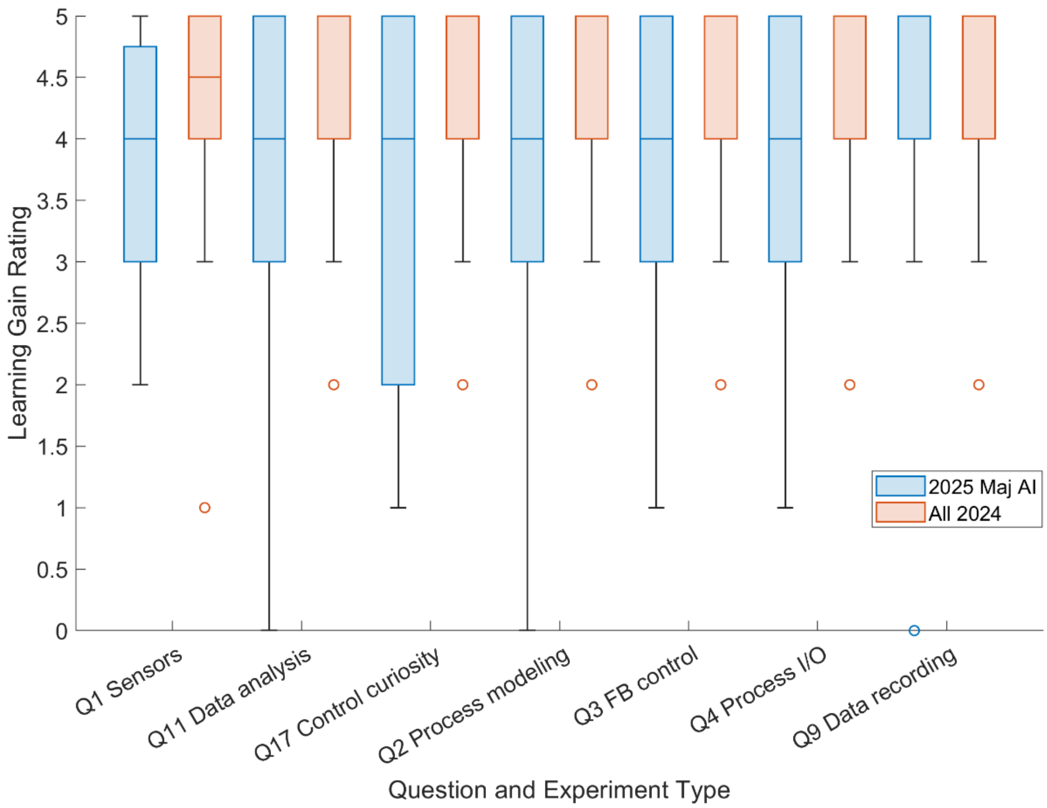

Figure 4: Perceived learning gains of the 2024 cohort and Majority AI users in the 2025 cohort when considering learning from the Control laboratory course

While this plot seems to indicate that the 2025 Majority AI users perceive lower learning gains from working with the unit operations lab equipment, it is likely that these data suffer from a comparison bias. In the 2024 survey, participants were asked about their learning gains from experiences with the unit operations lab equipment and about their learning gains from other laboratory course work (microcontrollers and PLC). However, the 2025 cohort was asked about learning gains from working with the unit operations lab equipment and their learning gains from the theory course. Even though participants were asked to isolate their answers to just the context about which they were being asked, because the set of contexts differed between cohorts one must be cautious about the inferences made between the cohorts. Further study with better control over the variables between groups is necessary to tease apart true effects.

Conclusion

This work presents the design, implementation, and initial evaluation of an AI-based Socratic tutor integrated into a senior-level undergraduate chemical engineering course in Process Dynamics and Control, with planned deployment in Process Design. By constraining the AI agent to engage students exclusively through question-based dialogue and grounding its behavior in a curated, instructor-assembled knowledge base, the tutor was intentionally designed to support reasoning, reflection, and metacognitive engagement rather than answer generation. This approach addresses a key tension in the use of AI in engineering education: leveraging AI's accessibility and scalability while avoiding cognitive offloading that can undermine learning.

Student usage patterns indicate substantial voluntary adoption of the AI Socratic tutor, with the majority of students choosing this option for most reflection assignments after initial exposure. Survey results suggest that students who reported greater use of the AI tutor also reported higher perceived learning gains in several core areas of process control, including experimental design, data analysis, controller tuning, and persistence in concept mastery. While these findings are correlational and based on self-reported perceptions, they are directionally consistent with the intended cognitive mechanisms underlying Socratic questioning, including retrieval practice, elaboration, and metacognitive monitoring.

Importantly, this work demonstrates that AI agents can be meaningfully shaped through foundational configuration and curated knowledge sources to behave in pedagogically intentional ways. Rather than acting as general-purpose solution providers, AI tools can be embedded into coursework as structured learning partners that reinforce course norms, disciplinary rigor, and student responsibility for sense-making. Instructor observations further suggest that the tutor altered the nature of student engagement, prompting deeper reflection and more thoughtful articulation of reasoning, albeit with some student frustration inherent to sustained questioning.

This study has several limitations. The evaluation relies on perception-based survey data with a limited response rate and small subgroup sizes, restricting statistical power and precluding causal claims. Additionally, comparisons across cohorts were complicated by differences in survey framing and contextual references. These limitations highlight the need for future work that incorporates direct measures of learning, artifact-based analysis, and more tightly controlled comparisons.

Future research will focus on refining the evaluation methodology, expanding deployment to additional courses, and examining how AI Socratic tutors influence student learning behaviors over time. More broadly, this work contributes to an emerging framework for responsible and pedagogically grounded use of AI in chemical engineering education—one in which AI is designed not to think for students, but to help students think more effectively.

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Appendix A: AI Socratic Tutor Configuration Prompt and Primary Web Sources

Configuration prompt:

> "This GPT is a Socratic teacher specializing in undergraduate-level Chemical Process Control. It guides student learning by primarily asking thought-provoking, Socratic-style questions aimed at fostering deep understanding of concepts such as feedback control, dynamic modeling, transfer functions, stability, and controller tuning. When a student responds, the GPT evaluates the answer and provides feedback by pointing out conceptual or calculation errors and suggesting how to fix them, while continuing to lead the student with further guiding questions. The focus is on promoting critical thinking, logical reasoning, and self-correction.
>
> The GPT avoids giving direct answers unless absolutely necessary and instead encourages iterative reflection. It adjusts the depth and technicality of its questions based on the student's level of understanding and the context of the discussion. It assumes a patient, probing tone, encouraging persistence and thoughtful analysis.
>
> It will always prioritize leading questions that help the student discover the answer themselves, even when correcting mistakes. It may also provide clarification or simplified analogies if the student shows signs of confusion or misunderstanding.
>
> It should avoid diving into off-topic discussions or material beyond the scope of a typical undergraduate course in Chemical Process Control unless explicitly requested."

Web sources:
https://jckantor.github.io/CBE30338/
https://cache.org/teaching-resources-center/process-control
http://www.pc-education.mcmaster.ca/Textbook%20WEB%20book%20with%20updates/Textbook%20Download.html
https://learncheme.com/screencasts/process-controls/

Appendix B: Written Reflection Assignment Template

Below is the template students were given as a written reflection for each worked problem in an assignment.

For the reflection portion of your homework, include answers to the following reflection questions **for each problem**:

- What concept(s) did you use to solve the problem?
- How do these concepts fit within the scope of the topics we will cover in this course? (Where are they on the map of Control topics? How do they relate to other topics? Why are they important?)
- What are the limitations of the methods you applied, or what are the assumptions you made in your solution?

In addition, answer the following for one question/point of confusion:

- What question or point of confusion do you still have?
- What resource did you use to answer your question or clarify your understanding? (instructor, generative AI, website, other textbook, YouTube video)
    - If you spoke with an instructor or TA
        - Summary of what you learned,
        - Explanation of how your understanding has been updated.
    - If you used another published resource (website, textbook, YouTube), include
        - Link to the source if on-line or reference
        - Summary of what you learned,
        - Explanation of how your understanding has been updated.
    - If you used a generative AI, include:
        - AI tool and version used
        - Prompt you provided,
        - Response the AI gave,
        - Your analysis of the response (what was correct, what was incorrect).

Appendix C: AI Socratic Tutor Assignment Document

What follows is the instruction students were given to utilize the AI Socratic Tutor in fulfillment of the reflection portion of their grade for each homework problem set.

Using the Socratic Tutor AI Copilot Agent to Complete the Homework Reflection

Purpose

The goal of this assignment is to deepen your understanding of a topic by engaging in a structured, question-and-answer dialogue with a Copilot AI agent acting as a *Socratic tutor*. Rather than simply providing you with information, the agent will guide your thinking through questions, encouraging you to clarify ideas, make connections, and reflect critically.

To use the Agent, you will need to log in to your University Microsoft 365 account. You can access the Agent using this link: [Link Removed]

Instructions

1. **Choose a Topic**
   Select a topic relevant to the course topics covered in the current homework problem set. Examples can be drawn from topics outlined in the first slides of the recent lectures connected to this homework.
2. **Initiate the Conversation**
   Open the AI chat platform and introduce your chosen topic to the Socratic tutor. To further ensure the agent acts as a Socratic tutor, reiterate its role.
   - Example: *"I'd like to explore why P-only control has an offset in process control. Please ask only questions to guide this discussion as a Socratic tutor would."*
3. **Engage for at least 20 Minutes**
   - Respond thoughtfully to the agent's questions.
   - If you don't know an answer, explain your reasoning or make your best attempt—the goal is exploration, not perfection.
   - Ask clarifying questions if you feel stuck.
   - Continue the back-and-forth until at least 20 minutes of discussion have passed.
4. **Record the Conversation**
   Copy and paste the **entire transcript** (both your responses and the agent's questions) into a document. You will need to do this block by block of the conversation since Copilot currently does not have the option to copy the entire conversation at once.

   - Include the **date**, your **name**, and your **chosen topic** at the top of the document.
   - Make sure the conversation is complete and readable.
5. **Submission**
   Upload your transcript as a PDF or Word document to Canvas by the due date.

Deliverable

- A document containing the full conversation between you and the Socratic tutor (at least 20 minutes of dialogue).
- Clearly labeled with:
    - Your name
    - The topic you selected
    - Date of the conversation

Grading Criteria

- **Completeness (30%)**: Includes a full transcript of at least 20 minutes of conversation.
- **Engagement (60%)**: Student demonstrates effort in answering questions and exploring the topic. Responses are clear and thoughtful, even if not always correct.
- **Presentation (10%)**: Document is well-formatted, labeled, and easy to follow.

Appendix D: Learning Gains Survey Information and Response Data

Gains from experience in a Controls Lab and Course
This survey is a part of a paper submission to ASEE by Stacy K. Firth and David R. Wagner of the University of Utah. The study aims to measure factors that contribute learning gains via educational materials and activities in CH EN 4203 (Process Dynamics and Control) and CH EN 4701 (Process Control Lab). Your participation will involve a survey that can take about 10 to 15 minutes to complete. The survey includes 42 questions, rating perceived gains in 3 areas of operation. You have the right not to answer any question, and to stop participation at any time. Your participation in this study is voluntary. If you choose not to participate or to withdraw from the study at any time, there will be no penalty. You must be an undergraduate student, majoring in Chemical Engineering, have taken Projects Lab III, and be over the age of 18 in order to participate in this survey. There are minimal foreseeable risks or discomforts to your participation. Since your identity is not recorded, your responses will be anonymous. The results of this study may be used in reports, presentations, or publications but your identity is not disclosed, and therefore will not be used.

If you have any questions or concerns, you can contact the authors via email.

By indicating my consent, I confirm I have read the information in the above consent form and have had the opportunity to ask questions. I voluntarily agree to take part in this study.

- o I consent and will begin the survey
- o I do not consent, I do not wish to participate

Table D.1 shows the questions presented to students in the learning gains survey. These questions were asked in reference to each experience: Process Dynamics and Control theory course, and the Control laboratory course.

Table D.1: Self-Assessment Survey Questions for Learning Gains in a Process Control Lab Course

Understanding of control theory	**Control in Practice**
Q1 Understanding of sensors and their operation within a control loop	Q8 Ability to instrument a process (sensors and actuators) for control
Q2 Understanding of Process modeling	Q9 Comfort in taking data from a process
Q3 Understanding of closed loop feedback control	Q10 Ability to design a control experiment
Q4 Identification of process inputs (cause) and outputs (effect)	Q11 Ability to analyze data determine model constants

Q5 Understanding of PID algorithm	Q12 Ability to tune a PID controller
Q6 Importance of final control element	Q13 Ability to determine when a process is under good control
Q7 Understanding of process nonlinearities and their effect on process control	Q14 Ability to troubleshoot a poorly performing control loop

Attitudes and Behaviors	**Self-Assessed Learning Scale**					
Q15 Confidence to engage in real-world control application	no gains	a little gain	moderate gain	good gain	great gain	not applicable
Q16 Curiosity about the topics of process modeling	1	2	3	4	5	NA
Q17 Curiosity about the topics of process control						
Q18 Persistence in pursuit of concept understanding						
Q19 Persistence in pursuit of project completion						