Research Article

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"What's Your Thinking behind That?" Exploring Why Biology Instructors Use Classroom Discourse

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Instructor discourse, defined as verbal interactions with students in the classroom, can play an important role in student learning. Instructors who use dialogic discourse invite students to develop their own ideas, and both students and the instructor share ideas in back-and-forth exchanges. This type of discourse is well-suited to facilitate deep learning for students but is rare in undergraduate biology classrooms. Understanding the reasoning that underlies the use of dialogic discourse can inform teaching professional development for instructors who are learning to use discourse to support student learning. Through classroom video recordings to identify dialogic discourse and stimulated recall interviews to elicit instructor reasoning, we investigated why undergraduate biology instructors used dialogic discourse in active-learning lessons. Using inductive and deductive qualitative analysis of interview transcripts, we identified and characterized seven reasons that instructors used dialogic discourse, including three aligned with a theoretical framework of student cognitive engagement and four that emerged from our data set. In addition to aiming to prompt generative cognitive engagement in 34% of instances of dialogic discourse, instructors used dialogic discourse to prompt activity, supply information, provide feedback, decipher student thinking, leverage student thinking, and cue students to make connections. Reasoning varied across different types of dialogic discourse. These findings provide valuable insights that can inform research, teaching professional development, and individual instructors' reflections.

KEYWORDS discourse, active learning, undergraduate, biology, instructor thinking, instructional practices, instructor reasoning

INTRODUCTION

Teacher discourse consists of instructors' verbal communications in the classroom to support student understanding of lesson content (1). Teacher discourse can be directed at the class as a whole, at a small group, or at individual students. Discourse can be dialogic or authoritative (2, 3). Dialogic discourse invites students to develop their own ideas, and both students and the instructor share ideas in back-and-forth exchanges. Table 1 describes types of dialogic discourse. Examples of dialogic discourse include an instructor asking students to explain their reasoning, evaluate another student's ideas, or interpret data (1, 4). Authoritative discourse focuses on instructor's ideas, is primarily unidirectional, and does not explicitly create space for students to develop their ideas (1, 3). An instructor uses authoritative discourse when they share information, answer a student's question, offer an evaluation of a student answer, or ask for factual recall (1). Students in classrooms that regularly and effectively use dialogic discourse can achieve higher learning gains and more student engagement than classrooms that rely primarily on authoritative discourse (5, 6).

Discourse can be important to active-learning instruction, because it communicates to students the expectations for the work they will do during class. Chi and Wylie (8) provided a framework for the cognitive work that students do during active-learning instruction. This framework, called ICAP, which is also useful for considering the goal of teacher discourse, differentiates the cognitive level of the work students are asked to do into four levels: interactive (I), constructive (C), active (A), and passive (P) (Fig. 1).

Interactive (I) and constructive (C) cognitive engagement occur when students generate a product that goes beyond the learning materials, either collaboratively building on each other's ideas or individually, respectively (8). Together, these two highest levels of cognitive engagement are referred to as generative cognitive engagement, and this term will be used here. For example, a student engages in generative cognitive engagement when they justify an answer with reasoning, interpret data they have not encountered before, or debate a topic with a peer. Following generative cognitive engagement, active cognitive engagement (A) involves physical manipulation and recall, and passive engagement (P) involves listening. Generative cognitive engagement results in deeper learning than active or passive cognitive engagement (8, 9). Though generative

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TABLE 1
Types of dialogic discourse, including definitions and examples[a]

Type of dialogic discourse	Description	Example discourse from our participants
Clarifying	Teacher asks student to elaborate on condensed, cryptic, or inexplicit statement	"You've got to elaborate. What's two separate things?"
Connecting	Teacher asks student to associate past topic to current topic	"What structure from the gustatory system do the cilia remind us of? You want to draw a lot of parallels here between the systems."
Contextualizing	Teacher asks students to relate idea to conventional knowledge, broader perspective, and their personal experiences	"What causes mucus and causes you to have a loss of smell or reduction in your ability to smell? What season has just passed us?"
Constructing	Teacher asks students to build knowledge by interpreting and/or making judgments based on evidence, data, and/or model	"How would you interpret that? What are the key takeaways from this sort of bimodal distribution?"
Requesting	Teacher asks students to justify or explain their reasoning	"What's your thinking behind that?"
Challenging	Teacher asks student to evaluate another student's ideas	"How many people agreed with [student's] order of responses? Did anyone have a different order that they're willing to share?"
Explaining	Teacher asks students to explain reasoning to other students	"Have a quick chat with your neighbor. See what you think and see if you can persuade somebody to change their mind."
Representing	Teacher asks students to create a visual or mathematical representation of content	"So how do we represent a genotype? What are you writing down to represent the genotype?"

[a]See reference 7 for further details.

cognitive engagement has greater potential for supporting deep student learning than active or passive engagement, not all active-learning lessons focus on generative engagement (10).

Dialogic discourse can be used by undergraduate instructors to prompt generative cognitive engagement, because this type of discourse focuses on students developing and sharing their own ideas (1). Yet, recent research suggests that dialogic discourse is rare in undergraduate biology courses, even those that include active approaches (1, 4). A national examination of 20 undergraduate biology classrooms (1) found that instructors used authoritative discourse for the majority of a class, even when the instructor had stopped lecturing and asked students to work. Dialogic discourse was equally uncommon in small and large courses (1). Therefore, there is an opportunity to benefit students by increasing the use of dialogic discourse in classes of all sizes.

Supporting undergraduate instructors to effectively use evidence-based instructional strategies, like dialogic discourse, often requires long-term teaching professional development that is focused on expanding instructor's ways of thinking about teaching and learning (11). These efforts benefit from insights about instructors' reasoning, so that professional development builds on what instructors already know and do. Therefore, we aimed to understand why instructors use dialogic discourse. We asked this research question: What reasons underlie the use of dialogic discourse among undergraduate biology instructors? We were interested in whether instructors used dialogic discourse with the specific intention of prompting generative cognitive engagement among students. Given a lack of prior research examining instructor reasoning for dialogic discourse, it was most appropriate to conduct exploratory rather than hypothesis-testing research. Instructional practices directly create learning environments for students, and instructors' reasoning influences the implementation of instructional practices. Thus, instructors' reasoning about teaching ultimately impacts students (10, 12–14). We must explore instructors' practices and reasoning if we are to realize the considerable potential of evidence-based instructional strategies for improving student outcomes.

METHODS

Ethics statement

This work was conducted with approval from the institutional review board at the University of Georgia, Athens (PROJECT00000297).

Participants

We recruited 22 college biology instructors who used active-learning strategies in courses with 50 to 270 students. Participants taught at 11 institutions across the United States, including 7 minority-serving institutions. These institutions included master's colleges and universities and institutions with high and very high research activity (15). The courses taught by

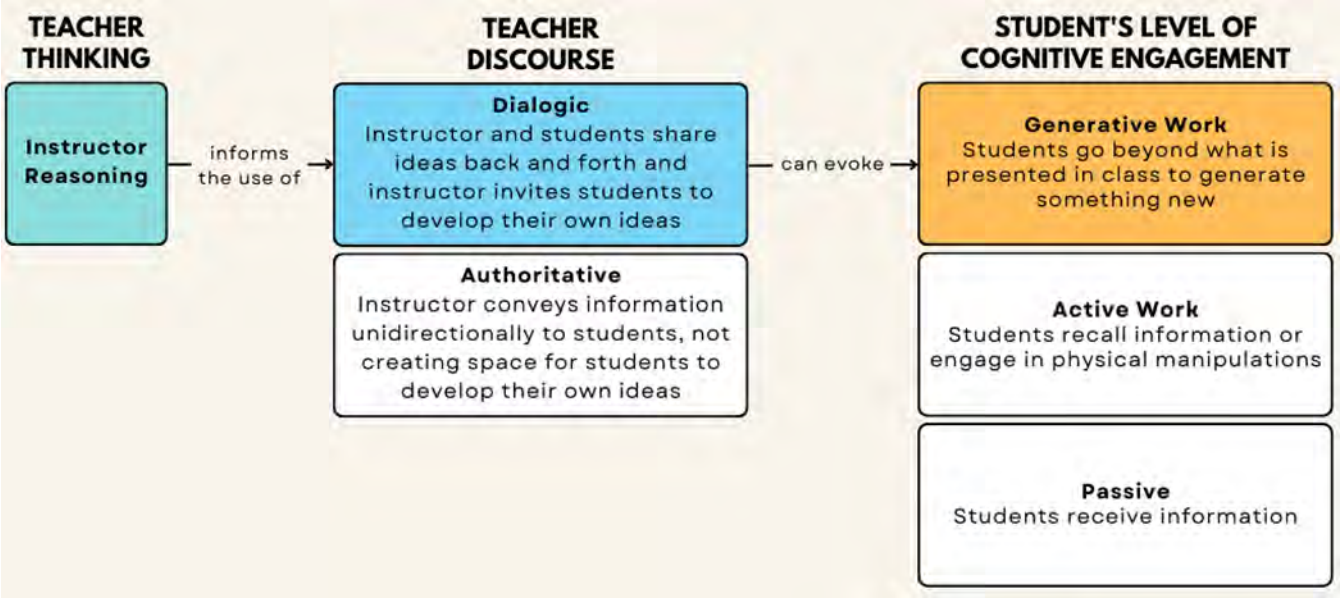

FIG 1. An overview of the conceptual framework for this study. This study examines what reasoning underlies the use of dialogic discourse by undergraduate biology instructors, and whether this reasoning relates to prompting generative work. Teacher discourse can be dialogic or authoritative (2, 3). Students' level of cognitive engagement can be generative, active, or passive (8). Generative work encompasses interactive and constructive cognitive engagement.

participants were all lecture sections rather than lab or recitation sections and included 18 introductory life sciences courses and 4 upper-division life sciences courses. Participants held both tenure track and non-tenure track faculty positions and had 1 to 20 years of teaching experience. We recruited participants via e-mail, and participants either self-identified as an active-learning instructor or were identified by a colleague as an active-learning instructor. Analysis of class recordings confirmed that all participants engaged students in some planned activity in addition to lecturing. We provided all participants with a monetary research incentive for their participation.

Data collection and analysis

This study involved collecting video recordings of lessons to identify instances of discourse and conducting interviews to elicit the reasoning behind participants' dialogic discourse.

(i) Analyzing discourse using videos and the CDOP. We video-recorded one class session for each participant to identify instances of dialogic discourse. We placed a camera in the back of the classroom and outfitted participants with a lapel microphone. We selected video clips totaling ~8 min from each lesson, prioritizing instructor-student interactions, and used these clips to elicit instructor thinking. We also systematically analyzed each video clip using the dialogic discourse codes from the classroom discourse observation protocol (CDOP) (Table 1) (1). Two coders independently analyzed each clip to identify all instances of dialogic discourse and then discussed any discrepancies to consensus.

(ii) Analyzing rationales for discourse using stimulated recall interviews and qualitative content analysis. We used stimulated recall interviews and qualitative content analysis (16) to uncover the reasoning behind participants' use of dialogic discourse. Stimulated recall interviews can reveal what participants were thinking while they were teaching (17). Within ~24 h after the video-recorded lesson, we conducted a stimulated recall interview in which we showed the participant one clip at a time and asked them to share everything they could recall thinking during the time period shown in the clip. Interviews were transcribed verbatim.

We next identified the segments of the interview transcripts that communicated a participant's rationale for each instance of dialogic discourse. Two coders independently read each transcript and identified segments displaying reasoning about each instance of dialogic discourse. For example, if clarifying discourse occurred in a video clip, we read the interview for evidence of the reasoning behind that instance of clarifying. We identified 59 instances of dialogic discourse for which participants shared their reasoning.

Next, we characterized the reasoning that participants provided for each instance of dialogic discourse, using both deductive and inductive qualitative content analysis. Each researcher independently summarized a participant's reasoning for one instance of discourse and then researchers discussed and constructed a consensus summary. We then examined all summaries of reasoning together to begin to identify distinct reasons offered by participants. Using a deductive approach, we relied on the ICAP framework as a lens to identify evidence of rationales that focused on generative, active, and passive cognitive engagement (8). We also used an inductive approach in which we remained open to reasoning that participants shared that went beyond the scope of the ICAP framework. Our analysis was iterative and collaborative. We coded and recoded data as our understanding of instructors' reasons evolved, always

TABLE 2
Count of participants who provided each reason for using dialogic discourse, by type[a]

Rationale[b]	Discourse type						
	Clarify (*n* = 12[c])	Connect (*n* = 6)	Contextualize (*n* = 4)	Construct (*n* = 20)	Request (*n* = 9)	Challenge (*n* = 5)	Explain (*n* = 2)
Generative	0	2	0	13	2	1	2
Active	2	0	0	2	0	0	0
Passive	6	1	0	6	4	0	0
Feedback	0	1	0	1	1	0	1
Deciphering ST	5	0	0	0	1	0	0
Leveraging ST	0	0	2	4	6	5	0
Cue connections	1	6	3	3	1	0	0

[a]The one instance of representing discourse had a passive rationale.
[b]The first three reasons align with the ICAP framework, and the next three emerged from inductive analysis.
[c]Numbers in each column exceed count because some participants provided more than one rationale for one instance of discourse.

coding independently first and then discussing to reach consensus. The outcome of our analyses was a list of reasons, described in detail. We also counted how frequently participants provided each reason for each type of dialogic discourse.

Limitations

There were a few limitations of this study. First, these data were collected as part of a larger study about teacher thinking and practice. As a result, video clips may not have included every instance of dialogic discourse that occurred in a lesson, and interviewers may not have always prioritized eliciting the rationale for dialogic discourse. Therefore, we did not compare the frequency of discourse in these lessons to the results of studies that analyzed entire class periods. Additionally, the participants in this study self-identified as using active-learning instruction and were willing to participate in a research study that required several hours of their time. As a result, these participants are unlikely to be representative of biology faculty more generally. Finally, classrooms are complex social environments and instructors make decisions for many reasons, which they may or may not be able to fully articulate (18). Therefore, the absence of a reason for an instance of discourse should be interpreted as a lack of evidence that this particular reasoning was salient to the instructor at the time of the interview. We cannot rule out the possibility that an instructor had additional reasons that they did not share. Given the lack of prior research about the thinking that underlies discourse among college science, technology, engineering, and math (STEM) instructors, this exploratory study could still offer novel insights.

RESULTS

We identified 59 instances in which participants used dialogic discourse and explained their reasoning for this practice. Participants provided seven reasons that they used dialogic discourse, which we characterize below. The first three reasons (generative engagement, active engagement, and passive engagement) are aligned with the ICAP framework (Fig. 1) (8). The other four reasons that participants provided (provide feedback, decipher student thinking, leverage student thinking, and cue connections) emerged from inductive analyses and are not within the bounds of the ICAP framework. Overall, the relationships between the types of dialogic discourse and instructor reasoning were complex. Collectively, the sample of participants offered at least three reasons for each type of dialogic discourse that occurred more than twice in the data set (Table 2). Individually, participants had more than one reason for an instance of discourse 32% of the time. We characterized participant's reasoning for using dialogic discourse by drawing on their words. Everything included in quotations was said by participants, some of which has been lightly edited for grammar.

Using dialogic discourse to prompt generative engagement

Of 59 instances of dialogic discourse, participants aimed to prompt generative work in 20 (34%). This was notable, because dialogic discourse engages students in back-and-forth dialogue in which they make substantive contributions, which is an example of generative cognitive engagement. Yet, in this data set, prompting generative cognitive engagement was the most common instructor rationale for only two types of discourse, constructing and explaining discourse, and explaining discourse was rare (Table 2). For every other type of discourse, participants more commonly provided other rationales that were not about engaging students in generative work.

Participants described three types of generative cognitive engagement they aimed to elicit with dialogic discourse, asking students to explain their reasoning, apply knowledge in a new situation, and use scientific thinking skills. One participant aimed for students to be "not just giving an answer" but

"having to explain why they've given that answer to their friend." A participant who used explaining discourse elaborated about why they wanted students to explain their reasoning like this, "[being] able to explain succinctly and accurately is one of the best ways to learn. . . and remember." Other participants aimed to engage students in specific scientific thinking, such as analyzing and interpreting evidence. For example, one participant used constructing discourse to try "to make [students] interpret the figure and come up with the answer on their own" and "make the prediction themselves." As these quotes illustrate, participants who used discourse to prompt generative work wanted their students to produce explanations and interpretations themselves, rather than being provided with these insights.

Using dialogic discourse to prompt active engagement

Some participants used dialogic discourse in order to get students engaged in something besides listening but fell short of aiming for generative work. This rationale aligns with active cognitive engagement, because the instructor intended for students to actively do something, rather than passively listening (8). This rationale was less common than others and used for just two types of discourse (Table 2). Participants with this reasoning hoped that their discourse would "get [students] engaged." One participant using clarifying discourse explained, "I'm not giving him the answers, but I'm helping him kind of process it, put it together in his mind." Another participant described using constructing discourse in order to do "something more exciting than me just talking to them more."

Using dialogic discourse to prompt passive engagement

Some participants used dialogic discourse to supply students with particular information. This rationale aligns with passive cognitive engagement in the ICAP framework, because students are meant to listen and not explicitly participate in learning in these moments (8). Importantly, this rationale is not aligned with the definition of dialogic discourse, which specifies that students contribute their own ideas in back-and-forth dialogue. Nonetheless, participants used five types of dialogic discourse with the goal of supplying information and offering hints, and this was the most common reason given for clarifying discourse (Table 2). Participants focused on prompting passive engagement explained that they used discourse to "throw out hints," "scoot them along," or "get them started" when working with a struggling student. For example, one participant explained the reasoning behind their clarifying discourse this way, "This is that idea of a leading question, because if they just come up empty handed with an answer, you have to give them something to pull them along."

Using dialogic discourse to provide feedback

In a few cases, participants used dialogic discourse, in part, to provide students with feedback about their thinking. This reasoning always accompanied a rationale aligned with the ICAP framework (e.g., generative, active, passive). One participant explained that their requesting discourse resulted in students receiving feedback, because everyone heard a student share an accurate explanation, which helped "to make sure that everybody was on the same page and could see where the error in their thinking was."

Using dialogic discourse to decipher student thinking

Participants also used dialogic discourse to clear up what a student meant by something they had shared. This reasoning is outside the bounds of the ICAP framework. Participants primarily provided this reasoning for clarifying discourse (Table 2), which makes sense given the definition of clarifying discourse (Table 1). For example, here a participant described how they struggled to understand a student's initial answer to a question and used clarifying discourse to follow-up: "I was just trying to understand what he was saying because the way he said it initially didn't register. . . I was trying to just clarify what his answer was."

Using dialogic discourse to leverage student thinking

Participants also used dialogic discourse to elicit and respond to students' ideas to further a lesson. This reasoning is also outside the bounds of the ICAP framework. Participants most often relied on constructing, requesting, or challenging discourse to achieve this goal (Table 2). In fact, this was the reasoning behind every instance of challenging discourse and two-thirds of requesting discourse (Table 2). Some participants who offered this rationale aimed to extract more in-depth information about students' thought processes. For example, one participant explained their requesting discourse by saying, "I asked him to talk me through the process he went through in answering." Some participants who offered this reasoning anticipated that students had particular "misconceptions" or "prior knowledge" and used discourse to "access" those ideas so that they could then be used in a class discussion or so the instructor could "clear up any misconceptions" that students expressed. One participant who used constructing discourse explained that they wanted to hear from more students in a discussion, because "I was hoping there'd be some wrong answers thrown out." In cases like these, participants thought students would learn from considering a range of ideas shared by their peers, including more and less accurate ideas.

Using dialogic discourse to help students make connections

Participants used dialogic discourse to support students in making connections between lessons and topics, which is another rationale that is not clearly aligned with the ICAP framework. Unsurprisingly, participants commonly provided this rationale for the two types of discourse that involved asking students to make connections: connecting and contextualizing (Table 2). For example, one participant used

TABLE 3
Ideas for those who want to advance the use of dialogic discourse

Goal	Suggested actions
Make an initial assessment of how you use teacher discourse in your classroom	• Audio-record yourself for a class period. This can be done using a smartphone's voice memo application and placing your phone in your pocket.
	• Identify instances of authoritative and dialogic discourse in the recorded class period using Table 1 and reference 7. This could be done alone or by swapping recordings with a peer.
	• Keep in mind that STEM instructors can use dialogic discourse in small and large classes and in introductory and upper-division courses (4).
Take your discourse to the next level	• Identify three places in a recorded lesson that you could have used dialogic discourse instead of authoritative discourse. Based on what you observe, strategize about how you can add more dialogic discourse to your next class period.
	• Consider why you used each instance of discourse and whether a type of dialogic discourse could better meet your objectives.
Try out specific types of dialogic discourse	• Brainstorm opportunities for using constructive dialogic discourse in your course. This was most commonly used by our participants and was often meant to prompt generative work.
	• Find an opportunity to add requesting discourse. Requesting discourse can be added as a response to an idea a student shares. Participants commonly used requesting discourse to leverage student thinking.
	• Find an opportunity to use challenging discourse. Challenging discourse can feel fraught because it involves asking students to evaluate one another's ideas. Instructors may worry about dissuading students from sharing ideas in the future. Yet, this discourse was valuable to participants in their efforts to leverage student thinking. One example of challenging discourse could be: "Who can build on what [student's name] was thinking? What ideas do you want to upvote or add on to? What alternatives should we consider?" It is important to use challenging discourse in response to ideas with a range of accuracy and completeness so students do not think that evaluation is only invited when answers need improvement.

connecting discourse because they were "trying to get students to recall information from previous classes to remind them that all the information is interconnected." Another participant used connecting discourse to try to help students "make connections with the content and things that they experience" because it would "help them retain it better."

DISCUSSION

This study aimed to explore why undergraduate biology instructors use dialogic discourse in their classrooms. Here, we discuss key findings, propose implications for future research, and share ideas about advancing teacher discourse for biology faculty and teaching professional developers.

Though dialogic teacher discourse can prompt students to engage in generative cognitive work and thereby facilitate deeper learning (Fig. 1), often participants had other reasons for using this discourse (Table 2). In fact, participants used dialogic discourse to transmit information almost as often as to prompt generative work (Table 2). This is evidence of a lack of alignment between instructor reasoning and teaching practice. Instructors are using evidence-based teaching strategies but not for their intended purposes. As discussed below, this raises questions about how student learning is impacted by these practices.

Importantly, participants had potentially fruitful reasons for using dialogic discourse beyond prompting generative work. One of the most common reasons for using dialogic discourse was to leverage student thinking. Specifically, participants used contextualizing, requesting, challenging, and constructing discourse with the goal of leveraging student thinking. These participants aimed to elicit students' ideas, which they then used to learn about student thought processes or to incorporate students' ideas into class discussions. Instructors who regularly leverage student thinking can improve student learning, create more equitable participation, and support the development of specialized teaching knowledge, even in large classes (100 to 300 students) (19–23).

This study has implications for future research about teacher discourse and instructor reasoning. First, given that instructors may have a wide range of reasons for using dialogic discourse, we need additional investigation of the impact of dialogic discourse on student cognitive engagement. If instructors' rationales for dialogic discourse are not focused on prompting generative cognitive engagement, are students still doing generative work? It is possible that dialogic discourse used without aligned underlying reasoning is subtly different and is not achieving the promised benefits for students. Second, we suggest that discourse researchers reconsider whether clarifying discourse should be considered dialogic. In this study, clarifying discourse was often employed to passively supply students with

information or to decipher their answers (Table 2). Given this, we hypothesize that clarifying discourse does not reliably prompt substantive dialogue between the student and instructor. Third, additional work should examine the relationship between discourse and leveraging student thinking. Does dialogic discourse follow from a desire to elicit and use student thinking? Or could experimenting with dialogic discourse lead instructors to place more value on or more frequently use students' ideas in their teaching?

This study, alongside other research about teacher discourse, has implications for biology faculty and professional developers who support faculty. Given the potential of dialogic discourse to prompt generative cognitive engagement, which in turn facilitates deep learning (8) (Fig. 1), it is worth interrogating how we can better use discourse in our own classrooms. Table 3 provides ideas for those who want to advance their use of dialogic discourse. These same ideas could also form the outline for a workshop or consultation plan for teaching professional developers who want to support faculty in using dialogic discourse.

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REFERENCES

1. Kranzfelder P, Bankers-Fulbright JL, García-Ojeda ME, Melloy M, Mohammed S, Warfa A-RM. 2020. Undergraduate biology instructors still use mostly teacher-centered discourse even when teaching with active learning strategies. Bioscience 70:901–913. https://doi.org/10.1093/biosci/biaa077.
2. O'Connor C, Michaels S. 2007. When is dialogue 'dialogic'? Hum Dev 50:275–285. https://doi.org/10.1159/000106415.
3. Scott PH, Mortimer EF, Aguiar OG. 2006. The tension between authoritative and dialogic discourse: a fundamental characteristic of meaning making interactions in high school science lessons. Sci Educ 90:605–631. https://doi.org/10.1002/sce.20131.
4. Alkhouri JS, Donham C, Pusey TS, Signorini A, Stivers AH, Kranzfelder P. 2021. Look who's talking: teaching and discourse practices across discipline, position, experience, and class size in STEM college classrooms. Bioscience 71:1063–1078. https://doi.org/10.1093/biosci/biab077.
5. Böheim R, Schnitzler K, Gröschner A, Weil M, Knogler M, Schindler A-K, Alles M, Seidel T. 2021. How changes in teachers' dialogic discourse practice relate to changes in students' activation, motivation and cognitive engagement. Learn Culture Soc Interact 28:100450. https://doi.org/10.1016/j.lcsi.2020.100450.
6. O'Connor C, Michaels S, Chapin S, Harbaugh AG. 2017. The silent and the vocal: participation and learning in whole-class discussion. Learn Instruct 48:5–13. https://doi.org/10.1016/j.learninstruc.2016.11.003.
7. Kranzfelder P, Bankers-Fulbright JL, García-Ojeda ME, Melloy M, Mohammed S, Warfa A-RM. 2019. The classroom discourse observation protocol (CDOP): a quantitative method for characterizing teacher discourse moves in undergraduate STEM learning environments. PLoS One 14:e0219019. https://doi.org/10.1371/journal.pone.0219019.
8. Chi MT, Wylie R. 2014. The ICAP framework: linking cognitive engagement to active learning outcomes. Educ Psychol 49:219–243. https://doi.org/10.1080/00461520.2014.965823.
9. Menekse M, Stump GS, Krause S, Chi MT. 2013. Differentiated overt learning activities for effective instruction in engineering classrooms. J Eng Educ 102:346–374. https://doi.org/10.1002/jee.20021.
10. Andrews TC, Auerbach AJJ, Grant EF. 2019. Exploring the relationship between teacher knowledge and active-learning implementation in large college biology courses. CBE Life Sci Educ 18:ar48. https://doi.org/10.1187/cbe.19-01-0010.
11. Henderson C, Beach A, Finkelstein N. 2011. Facilitating change in undergraduate STEM instructional practices: an analytic review of the literature. J Res Sci Teach 48:952–984. https://doi.org/10.1002/tea.20439.
12. Offerdahl EG, McConnell M, Boyer J. 2018. Can I have your recipe? Using a fidelity of implementation (FOI) framework to identify the key ingredients of formative assessment for learning. CBE Life Sci Educ 17:es16. https://doi.org/10.1187/cbe.18-02-0029.
13. Stains M, Vickrey T. 2017. Fidelity of implementation: an overlooked yet critical construct to establish effectiveness of evidence-based instructional practices. CBE Life Sci Educe 16:rm1. https://doi.org/10.1187/cbe.16-03-0113.
14. Wiltbank L, Williams K, Salter R, Marciniak L, Sederstrom E, McConnell M, Offerdahl E, Boyer J, Momsen J. 2019. Student perceptions and use of feedback during active learning: a new model from repeated stimulated recall interviews. Assess Eval Higher Educ 44:431–448. https://doi.org/10.1080/02602938.2018.1516731.
15. American Council on Education. 2022. Carnegie classification of institutions of higher education https://carnegieclassifications.acenet.edu/classification_descriptions/basic.php.
16. Miles MB, Huberman AM, Saldaña J. 2018. Qualitative data analysis: a methods sourcebook. Sage Publications, Thousand Oaks, CA.
17. Calderhead J. 1981. Stimulated recall: a method for research on teaching. Br J Educ Psychol 51:211–217. https://doi.org/10.1111/j.2044-8279.1981.tb02474.x.
18. Loughran JJ. 2004. A history and context of self-study of teaching and teacher education practices, p 7–39. *In* Loughran JJ,

Hamilton ML, LaBoskey VK, Russell T (ed), International handbook of self-study of teaching and teacher education practices. Springer, Dordrecht, Netherlands.
19. Carpenter TP, Fennema E, Peterson PL, Chiang C-P, Loef M. 1989. Using knowledge of children's mathematics thinking in classroom teaching: an experimental study. Am Educ Res J 26:499–531. https://doi.org/10.3102/00028312026004499.
20. Franke ML, Carpenter TP, Levi L, Fennema E. 2001. Capturing teachers' generative change: a follow-up study of professional development in mathematics. Am Educ Res J 38:653–689. https://doi.org/10.3102/00028312038003653.
21. Kim H-j. 2019. Teacher learning opportunities provided by implementing formative assessment lessons: becoming responsive to student mathematical thinking. Int J Sci Math Educ 17:341–363. https://doi.org/10.1007/s10763-017-9866-7.
22. Richards J, Robertson AD. 2015. A review of the research on responsive teaching in science and mathematics, p 54–73. *In* Robertson AD, Scherr RE, Hammer D (ed), Responsive teaching in science and mathematics. Routledge, New York, NY.
23. Gehrtz J, Brantner M, Andrews TC. 2022. How are undergraduate STEM instructors leveraging student thinking? Int J STEM Educ 9:18. https://doi.org/10.1186/s40594-022-00336-0.