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Exploring the Complexity of Adaptive Teaching Expertise within Knowledge Generation Environments

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Abstract: The shift towards Next Generation Science Standards represents a paradigmatic change in teaching, transitioning from knowledge transmission to knowledge generation approaches. This reform underscores the complexity of teaching expertise, extending beyond mere knowledge to require a profound comprehension of generative learning environments. In this study, we explore Adaptive Teaching Expertise (AdTex), defining it as a teacher's capacity characterized by fluidity and reflexiveness in teaching dynamics, rather than just flexibility. Through a complexity framing approach, we delineate three layers of AdTex: the visible actions of teachers, the semi-visible use of epistemic tools such as language, dialogue, and argument, and the tacit orientations towards learning that encompass epistemological, ontological, and axiological dimensions. Our research primarily investigates the intricate relationship between the epistemic tool and orientation layers. Our findings highlight the significance of an interconnected understanding and the impact of philosophical orientations on adaptive teaching practices. A notable contribution of this study is the development of a framework that articulates the belief and knowledge systems crucial for fostering generative learning environments, alongside the introduction of complexity maps to illustrate the interplay among these subsystems.

Keywords: Adaptive Teaching Expertise; epistemic tools; teacher orientations; knowledge generation approaches

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1. Introduction

The introduction of new national science standards, such as Next Generation Science Standards (NGSS), has triggered a paradigmatic shift in the concept of teaching, signaling a departure from the traditional model where teachers merely replicate instructional tasks [1]. The new vision emphasizes not only students' grasp of science concepts but also their understanding of how these concepts are generated through epistemic practices [2]. This shift acknowledges the limitations of teacher-centered pedagogies that primarily focus on transmitting knowledge [3]. Instead, it recognizes the complexity and interactivity of teaching, calling for the reframing of teaching expertise to better tackle the challenges associated with creating generative learning environments [4,5].

Defining teaching expertise has been a challenge in educational research, often failing to capture the dynamic essence of teaching [6]. Research has agreed that teaching expertise goes beyond content and pedagogical knowledge; it necessitates a deep understanding of learning environments where students actively participate in knowledge generation. In science education, this entails recognizing that learning environments are complex systems in which students utilize various forms of language (e.g., [7]), engage in argumentation (e.g., [8]), and participate in dialogical opportunities (e.g., [9]). To cultivate such environments, teachers must continuously adapt their methods and responsively address students' ideas, aligning their actions with the principles of knowledge generation approaches [10]. This capacity is what we refer to as Adaptive Teaching Expertise (AdTex).

Our understanding of adaptive expert teachers aligns with Berliner, who described expert teachers as individuals who "are not consciously deliberating what to attend to and what to do. They act effortlessly and fluidly, in a manner that is rational but not easily described as deductive or analytic behavior" [11] (p. 167). The unconscious *fluidity* in learning environments emerges when teachers embody a sense of *reflexivity*, as proposed by Schön [12], and willingly share their authority to navigate potential pathways leading to authorized big ideas [10]. This underscores the necessity for teachers to transcend the constraints of mere flexibility within established practices and strategies. AdTex is often defined as a departure from prescribed curricula or lesson plans [13,14], directing research toward the exploration of actions or decisions aimed at flexibly adjusting predefined practices and strategies already possessed by teachers. While we acknowledge that flexibility is undoubtedly seen as a hallmark of adaptive teaching, we contend that the concept of fluidity deserves greater attention for its potential to more accurately encapsulate the complex and unstructured nature of teaching in knowledge generation environments.

Developing AdTex is a complex journey, characterized by various challenges, tensions, and contradictions [10,15]. Understanding this complexity means recognizing the various processes, mechanisms, and elements at work and these components operate on multiple levels and in different directions, influencing teachers' intentions regarding their teaching methods and educational goals [16]. This suggests the need to shift from a linear perspective of teacher development to one that recognizes its multifaceted and nonlinear nature [17].

In our pursuit to comprehend and navigate the intricate dynamics of teacher development, we have adopted a complexity framing approach [18]. This approach posits that teacher development is not a simple outcome of predefined factors but rather results from a multifaceted interplay of various elements or systems [19]. Within our complexity framework, we delineate three distinct, yet interconnected systems arranged into layers of what we term as AdTex within generative learning environments (see Figure 1). These three layers consist of the following:

(1) ***Instructional Practice System (Visible layer)*:** This initial layer encompasses observable actions directly managed by teachers. It pertains to the tangible instructional activities and actions exhibited by teachers in the classroom. This layer is the one that is traditional examined by researchers.

(2) ***Epistemic Tool System (Semi-visible layer)*:** Situated just beneath the surface, this layer involves the language, dialogue, and argumentation framed and utilized by teachers. These tools are pivotal for fostering effective communication, stimulating critical thinking, and facilitating meaningful interactions within the science classroom. They are essential for implementing knowledge generation approaches such as Science Writing Heuristic (SWH) that align with the NGSS [20]. The utilization of these tools is often partially visible as they are intricately intertwined with epistemic practices. These tools are generally examined in isolation from each other.

(3) ***Orientations System (Invisible layer)*:** This third layer operates at a deeper level, encompassing unspoken beliefs and orientations towards learning that are embedded through teachers' actions. In our framework, it encompasses three philosophical orientations to learning: the epistemological, ontological, and axiological orientations. These orientations encompass a broad spectrum of beliefs regarding instructional approaches and serve as a lens through which we can scrutinize the principles and assumptions that underpin teachers' pedagogical approaches and decision-making processes [21,22].

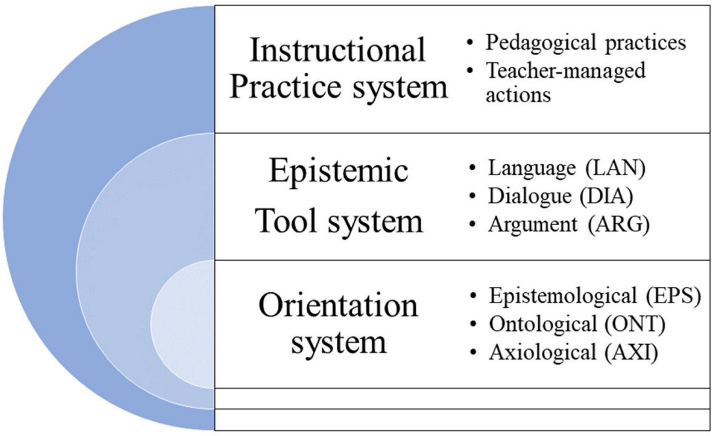


Figure 1. Complexity framework of AdTex.

Our primary objective in employing this framework is to suggest new ways to conceptualize and investigate key questions concerning teacher development of AdTex within knowledge generation environments. We aimed to challenge the assumptions commonly underlying research and practice related to the development of AdTex, which defines AdTex as the ability to adapt the pre-determined practices by flexibly using a set of knowledge and practices teachers already possess. By redefining AdTex as a complex system, the study seeks to shift away from traditional linear models of teacher development, which emphasizes predictable linear cause-and-effect relationships of pre-determined factors such as sets of knowledge and skills [16,23]. Instead, it views AdTex as a dynamic and evolving process, characterized by emerging patterns and phenomena resulting from multidimensional relationships and interactions among diverse elements and subsystems [18]. AdTex, in our perspective, is not a static state but an *evolving* process or *open* system where the whole is far more than the sum of its parts [24,25].

While we acknowledge the vast range of subsystems and factors influencing the development of AdTex, our initial investigation focused on the two subsystems: the Epistemic Tool system (Layer 2) and the Orientation system (Layer 3). From the three layers we outlined above, we chose to study these tacit layers because the interactions between these layers can display a continuum of complex and fluid thinking and actions, moving from simpler and routine to more generative and adaptive. The decision to focus on these two layers does not diminish the importance of the first, more visible layer of teacher actions. Instead, it reflects a strategic choice to delve deeper into the less observable aspects of teaching expertise that drive visible behaviors. This focus aims to uncover the foundational elements that enable the visible layer, thus providing a nuanced understanding of the interconnectedness of all layers.

2. Literature Review

2.1. The Development of Adaptive Teaching Expertise (AdTex)

AdTex is the capacity that enables teachers to adapt instructional decisions beyond set curriculum guidelines, recognizing the diverse cultural, linguistic, and cognitive resources and needs of learners [26]. It ultimately ensures equitable access to learning opportunities and promotes optimal learning outcomes [15,27]. In science education, the importance of developing AdTex is particularly pronounced due to the unique nature of the subject and the goals of science instruction [10,28]. Advocated by the Next Generation Science Standards [1], the classroom focus is now on cultivating knowledge generation and driving students to actively immerse in the learning process [2,29]. This vision involves emphasizing scientific inquiry, critical thinking, and the application of scientific practices which not only foster a deeper understanding of scientific concepts but also promote a sense of ownership in the learning process [30]. However, this approach demands teachers to be adaptive since they cannot ensure specific outcomes or change existing notions exactly as they might wish—highlighting a teacher's inherent "lack of direct control" over every classroom detail [31] (p. 69). Consequently, it is paramount for teachers to develop AdTex that enables them to create a generative environment by constantly adapting their curricula, adjusting dialogic interactions, and aligning their instructional methods with research-supported innovations all in compliance with the NGSS expectations [32].

To grasp the concept of AdTex, researchers often turn to the comparison between routine and adaptive expertise [33]. Routine expertise primarily revolves around the application of well-established skills and routines, aiming to achieve greater fluency and efficiency. It entails mastering the predictable aspects of teaching that can be anticipated and integrated into a teacher's toolbox. On the other hand, adaptive expertise surpasses routine proficiency and involves the ability to innovate, re-evaluate established practices, and adjust one's approaches when confronted with unique and unforeseen situations [34]. Adaptive expertise is frequently characterized by flexible, innovative, and creative competencies [35]. Nonetheless, we argue that the term *fluidity*, deeply rooted in a strong philosophical foundation and a profound understanding of fundamental learning tools, should be included as a core characteristic to capture the essence of adaptive teaching in knowledge generation environments [10]. Teachers with adaptive expertise engage in ongoing inquiry and consistently refine their knowledge and practices to align with their philosophical orientations. Impressively, they often make these refinements naturally, without overtly focusing on the individual practices being modified [36].

The development of AdTex requires a paradigm shift in teachers' perspectives. Timperley outlines a framework for this transition [36]. Central to this is shifting attention from oneself to prioritizing students. This transformation delves deeper into a teacher's core beliefs, placing emphasis on understanding each student's unique needs and perspectives. Teachers who are adept in this approach see education as a joint effort, building dynamic and responsive bonds with students and the entire learning community. This expanded viewpoint also demands a deeper grasp of teaching's nuances, encompassing the true nature of knowledge, the dynamics of teacher–student interactions, and the pivotal role teachers play in the learning process [36].

Historically, teacher training has predominantly focused on routine expertise and adhered to traditional implementation frameworks that prioritize fidelity, replication, and measurable outcomes. However, recent studies have highlighted the limitations of such approaches, overlooking the dynamic nature of teaching and the need for contextual adaptation [37]. To address these limitations, recent research suggests embracing a more holistic and adaptive approach to teaching expertise. This entails understanding the role of individuals' philosophical orientations toward learning and the dynamic interplay between the orientations and knowledge bases. The focus should extend beyond rigid fidelity and outcomes to particular perspectives of learning and include a nuanced understanding of teachers' beliefs, orientations, knowledge bases, and sense-making processes. By incorporating these perspectives, research on teaching expertise can evolve to better reflect the complex, dynamic, and contextual nature of effective teaching and learning [37].

In conclusion, the conceptualization and development of teaching expertise entails recognizing and delineating the distinction between routine and adaptive expertise. Teachers must transition their focus from the self to students and gain a deep appreciation for the multifaceted nature of teaching. We argue that teacher education programs should embrace these conceptual distinctions and move away from a narrow emphasis on routine expertise. Acknowledgement should be given to the importance of adaptive expertise and the dynamic nature of effective teaching, fostering a more comprehensive understanding of teaching expertise that aligns with the complexities of educational contexts.

2.2. Philosophical Orientations to Learning: Epistemological, Ontological, and Axiological

Teacher development is significantly influenced by various philosophical orientations toward learning, as evidenced by a range of scholarly works published in the past decades (e.g., [38–42]). In our own study, we have explored the roles of epistemic orientation in teacher development demonstrating its importance in the development of AdTex [10]. To build more complete pictures of the complexity, we began to explore teacher orientations beyond epistemology and identified three key orientations (i.e., epistemological, ontological, and axiological orientations) that contribute to teachers embracing knowledge generation approach in science [21]. This three-orientation framework was built based on the previous literature that has consistently demonstrated the interconnected and interdependent relationships between the epistemological and axiological domains [43,44], as well as the epistemological and ontological domains [45,46]. Our framework posits that these three orientations form interrelated and mutually dependent domains that profoundly shape teacher development. We argue that these domains form a system.

Epistemological orientations encompass an individual's beliefs and perspectives regarding the origin and acquisition of knowledge, and they have been extensively investigated in empirical studies [47–50]. The literature reveals a strong correlation between teachers' epistemological beliefs and their implementation practices in various disciplines [51–53]. Foundational principles for establishing knowledge-generation learning environments through an epistemological lens include orientations towards a rapidly evolving knowledge system, a dynamic curriculum that prioritizes student engagement, and the acquisition of subjective knowledge by connecting existing and new information derived from direct experiences [54,55].

Ontological orientations refer to one's beliefs about the nature of reality and existence, and scholars have increasingly explored their influence on teaching practices [49,56]. Research has indicated that teachers' ontological perspectives on learning play a crucial role in transitioning from traditional replicative learning environments to the implementation of knowledge-generation environments [45,57]. Generative ontological orientations involve the incorporation of sociocultural interaction in learning, acknowledging that individuals construct distinct realities within social contexts [45,58,59]. These orientations assume that students possess agency and control over their own learning, while also recognizing the role of teachers as co-participants and facilitators in the learning process [21,57,60].

Axiological orientations, as identified by Biesta, represent another philosophical perspective that significantly influences teacher development [61]. Axiology is viewed as a critical determining factor in shaping the goals and directions of education, and recent research has further underscored its importance [46]. Acknowledging the multidimensional nature of teacher development, scholars have emphasized the need to utilize various processes and mechanisms to support teachers' growth [62]. This includes the use of epistemic tools such as language, dialogue, and argumentation to navigate the complexities of teaching and learning [63]. Within generative science classrooms, axiological orientations prioritize the value of these epistemic tools as critical elements for fostering effective and transformative learning experiences [64–66].

We argue that these three orientations form a system, where the impact on one orientation subsystem has the potential to impact and change another subsystem.

2.3. Epistemic Tools for Learning Science: Language, Dialogue, and Argument

2.3.1. Language

Language is a fundamental tool for generating epistemic practices in scientific endeavors [7,67]. Its significance in science learning is multifaceted. As articulated in the National Research Council's (NRC) Framework document, every science or engineering lesson inherently entails a linguistic dimension, as students are expected to proficiently interpret textual meaning, articulate scientific ideas through written language and diagrams, and engage in extensive discourse concerning these ideas [29]. Furthermore, language serves as the gateway to accessing scientific concepts, as comprehending and ruminating upon scientific phenomena necessitates active engagement with the specialized language of science [67]. Hence, nurturing students' scientific literacy encompasses not only the foundational literacy skills required for reading and writing about science but also the cultivation of comprehensive knowledge and erudition in the domain itself [7].

In order to effectively harness language as an epistemic tool, teachers must recognize that language practices are intricately connected with other practices, such as dialogue and argumentation, which collectively frame the epistemic practices of science. Thus, it is essential to integrate these tools synergistically within science practices, rather than treating them as separate entities, enabling students to utilize them flexibly for presenting and critiquing their thoughts [68].

By emphasizing the interplay between language and scientific practices, teachers can foster an environment where students engage in active discourse, construct arguments, and communicate their ideas effectively. Language serves as a medium through which students can articulate their scientific inquiries, observations, and explanations, enabling them to deepen their understanding of scientific concepts and processes [68]. Moreover, the utilization of language in science education extends beyond verbal communication. It encompasses various modes of representation, including written text, diagrams, graphs, and mathematical symbols, among others. Proficiently using these diverse modes of language empowers students to convey their scientific knowledge comprehensively and cater to different learning styles [69].

In conclusion, language is an indispensable tool for learning science, as it facilitates the development of epistemic practices and enables effective communication of scientific ideas.

2.3.2. Dialogue

Understanding the role of dialogue in science learning is paramount due to its significant impact on student participation and the development of their epistemic agency, as underscored by Kelly [9] and Mercer [70]. Dialogue paves the way for students to articulate their understanding and reasoning clearly, fostering active involvement and in-depth engagement [71].

Furthermore, dialogue functions as a crucial tool for collective knowledge building within the classroom setting [72]. It transcends simple conversation by encouraging students to express their thoughts, challenge assumptions, and engage in critical thinking. This process nurtures a supportive, collaborative learning environment, making dialogue more than a pedagogical tool but a cornerstone of effective teaching and learning [73].

Moreover, dialogue is a tool for fostering student agency [9]. By crafting an environment that promotes collaborative discussions and knowledge construction, dialogue enriches students' understanding of the subject, sharpens their critical thinking skills, and enhances their ability to express ideas and create linkages between concepts [71]. It has been substantiated by various studies that dialogue aids in developing cognitive skills and deepening students' comprehension of scientific content. Therefore, an in-depth understanding of how teachers incorporate dialogue into their instruction is essential for promoting active learning and critical thinking among students.

2.3.3. Argument

Argumentation has been widely studied as an educational tool in science education, playing a crucial role in knowledge generation and fostering critical reasoning skills [74–76]. Walton defines the structure of an argument as presenting premises to support a conclusion with a persuasive or explanatory purpose [77].

There are three types of reasoning: abductive, inductive, and deductive. Abductive reasoning formulates the best possible explanation, inductive reasoning generalizes from specifics, and deductive reasoning works from general premises to a certain conclusion [78,79]. Nussbaum highlights that argumentation involves both cognitive processes and social interaction [80]. Pedagogical approaches like dialectical argumentation and accountable talk stress the value of argument and dialogue in learning [80–82]. It is recognized that the construction of arguments is inherently social and dependent on language [83].

Compared to traditional inquiry-based teaching, argument-based science inquiries such as the Science Writing Heuristic and Argument-Driven Inquiry place emphasis on students generating connections between questions, claims, and evidence [74,76]. Implementing argumentation in classrooms enhances conceptual understanding and critical thinking but also presents challenges, often due to the unclear argument structure [84]. This study will explore these complexities in science classrooms by investigating the relationships between teachers' philosophical orientations and epistemic tools.

Again, we see these three epistemic tools as a system, where the use of one tool has the potential to impact the other tools within the system.

2.4. Summary

A deeper and nuanced understanding of the complex relationships between a teacher's philosophical orientations, comprising epistemological, ontological, and axiological beliefs, and their utilization of dialogue, argument, and language in science education, is critical and urgent. Adopting a complexity in studying these two competing systems is important. These foundational systems serve as the backbone of classroom learning environments and knowledge generation, and play an instrumental role in influencing how students actively participate in their learning journey. The capacity of teachers to comprehend and navigate these interconnected elements is not merely an advantage; it is essential to foster active student engagement, promote critical thinking, and maximize the robust generation of knowledge within the science classroom. It is the significance of these elements that imparts urgency to this study. By employing complexity mapping, this study aims to delve into the multifaceted relationships between these critical aspects and illuminate the nature of teacher AdTex development. This endeavor is anticipated to offer invaluable insights that can significantly contribute to the understanding and improvement of science teacher education.

3. Materials and Methods

3.1. Context and Participants

The present study was undertaken within the framework of a larger research project (grant number blinded) with the objective of examining and defining AdTex in generative learning environments. Over a period of three years, a Professional Development (PD) program was implemented to support teachers' understanding and utilization of a knowledge generation approach called the SWH. The SWH approach, a form of inquiry-based approach to learning, emphasizes the importance of students engaging in authentic scientific practices, such as asking questions, conducting investigations, and constructing explanations based on evidence. It encourages students to write and communicate their scientific understanding, thereby deepening their conceptual knowledge and scientific literacy [74]. This approach necessitates a shift in the teacher's role from a traditional authority figure to one that is more reflective and responsive, qualities that are essential to developing adaptive teaching expertise.

With this objective in mind, PD sessions were held during the summers of 2019, 2020, and 2021, each lasting for four to five days. The focus of the PD sessions encompassed both learning theory and three key epistemic tools: language, dialogue, and argument. The PD sessions comprised various activities, including whole-group and small-group discussions centered around learning theory and conceptual comprehension of the epistemic tools. Furthermore, workshops were conducted to address the topic of student agency in controlling classroom language, dialogue, and argumentation. These workshops provided opportunities for teachers to discuss and explore strategies to empower students in these areas. Moreover, additional follow-up meetings were organized to facilitate ongoing conversations with teachers, specifically focusing on the planning and implementation of the SWH approach. These meetings served as a space for teachers to share their experiences, seek guidance, and collaboratively problem-solve to ensure effective integration of the SWH approach in their instructional practices. To provide further support, cluster leaders or graduate students made planned visits to observe teachers' instruction and engage in discussions with them, addressing challenges and successes encountered during the implementation of the SWH approach.

To explore the intricate connections between teachers' philosophical orientations and their use of epistemic tools, we gathered data from a multiple case study [85] involving 11 teachers. These teachers were deliberately chosen from a larger group participating in our PD program. Selection criteria included their full participation in all summer PD sessions and their willingness to engage in detailed data collection throughout the three-year project. The teachers, whose details are anonymized using pseudonyms in Table 1, hail from two different U.S. states—one in the Midwest and the other in the Southeast. Their teaching experience ranged from 1 to 26 years, and they were instructing students from third to fifth grade. Among the 11 teachers, nine were female and two were male. The deliberate choice was made to include teachers from a variety of residential locations, spanning rural, suburban, and urban areas. The school districts differed in terms of the number of students enrolled in each grade and the rates of free/reduced lunch. Every participant expressed personal interest in joining the PD program. While some teachers had curriculums promoted by the district, they clarified that they primarily used those curriculums as a reference rather than feeling obligated to follow them step-by-step.

Table 1. Participant information.

Teacher	Region	Community	Years of Teaching Experience	Grade Level	Gender (F: Female, M: Male)	District Enrollment by Grade	Economically Disadvantaged Rate (All Grades)	Curriculum (N: No Restrictions, D: District Prompted)	Commitment to PD (S: School Driven, P: Personal)
Lusia	Midwest	Suburban	13	3	F	214	38%	N	P
June	Southeast	Rural	12	5	F	186	80%	N	P
Teresa	Southeast	Urban	2	5	F	835	45%	N	P
Rose	Southeast	Urban	9	5	F	835	45%	N	P
Amber	Southeast	Suburban	15	5	F	2782	63%	D	P
Julie	Midwest	Rural	13	4	F	47	39%	N	P
Jordan	Midwest	Suburban	19	4	F	57	45%	N	P
Alex	Midwest	Urban	2	4	M	79	44%	N	P
Khloe	Midwest	Suburban	1	4	F	57	45%	N	P
Kennedy	Midwest	Rural	8	5	M	35	41%	N	P
Sophia	Southeast	Urban	26	4	F	797	45%	D	P

Note. The data on 'district enrollment by grade' and 'economically disadvantaged rate (all grades)' was accessed online via the public data set of each school district, representing the 2019–2020 academic year.

3.2. Data Collection Procedure

Data sources of the current study include vignettes, teacher reflections, interviews, and classroom videos obtained during the second and third years of the project. We chose this data set for analysis because it offers valuable episodes that have the potential to unveil the complex relationships between teachers' philosophical orientations and their understanding of epistemic tools.

3.2.1. Vignettes

We employed vignettes to evaluate teachers' adaptability and their beliefs regarding knowledge generation. As part of their involvement in the PD program, teachers were presented with four distinct short stories depicting a hypothetical individual. Each vignette contained specific prompts designed to elicit their orientations of learning and their understanding of language, dialogue, and argumentation. For instance, one vignette task involved the following situation: "Naomi completed a Science Writing Heuristic workshop last summer. She thinks her science teaching went okay this year, but she wants to make better use of language. Please describe to Naomi how she could think about language as she prepares. Include any steps she should take and make your thinking transparent, so she knows why those steps are important". We asked the teachers to write for ten minutes in response to the vignettes. We conducted the same vignette tasks twice, once in the summers of 2020 and 2021.

3.2.2. Written Reflections

To delve into the complexities of AdTex, we gathered an additional set of written data during the professional development sessions in the summers of 2020 and 2021. We posed several open-ended questions to encourage the teachers to reflect on their orientations to learning, the use of epistemic tools, and the changes they experienced in their knowledge and practices. Some examples of reflection questions were as follows: (1) What's been your biggest change in how you think about learning and teaching science? How would you like to grow in your practice? (2) What has been your biggest change in how you think about using language in science? (3) How do you build value and trust to create an environment that supports dialogue? (4) What was your biggest struggle with argument? What will you do/try in your classroom next year to support student argumentation?

3.2.3. Interviews

We also conducted two semi-structured interviews with teachers, one in Fall 2020 and another in Fall 2021. These interviews were designed to explore the teachers' orientation of learning, their knowledge and utilization of epistemic tools, adaptability, and planning. Here are a few examples of the questions asked during the interviews: (1) Do you think learning works in mostly similar ways across content areas, or do you think students learn differently from science to English language art, to math, to social studies? What does your view of learning mean in your teaching? (2) How can language contribute to student learning in science and in other content areas? In your mind, what is the ultimate goal of language use? (3) How much do you stick to a daily or unit plan, and how much do you deviate? How does this compare to what you have done in the past? The interviews were conducted by graduate students and a post-doctoral researcher, either via Zoom or in person. Typically, they lasted between 25 and 50 min. All sessions were audio recorded and subsequently transcribed.

3.2.4. Classroom Videos

To enhance our comprehension of the semi-visible dimensions of adaptive teaching, we undertook an analysis of classroom video recordings from the Fall of 2020. Considering the adjustments required by the COVID-19 pandemic, we solicited a subset of teachers to document one of their science instruction sessions and forward these recordings to our research team for examination.

3.3. Data Analysis

To delve into the relationship between Layer 2 (Epistemic Tool System) and Layer 3 (Orientation System), we undertook two main analyses: (1) Complexity mapping, and (2) Power and Agency Analysis for Epistemic Tools (see Figure 2). The purpose of the complexity mapping was to uncover hidden aspects of the system. Specifically, it aimed to spotlight the ties between the three orientations and the understanding of epistemic tools. On the other hand, the Power and Agency analysis sought to highlight the more visible aspects of epistemic tool system which is the representation of how the tool use is reflected in learning environments. By merging insight from these two analyses, we were able to gain a more complete picture of how Layer 2 and 3 interrelate.

Our first main analysis process consisted of four stages: (1) creating two-dimensional profiles based on teachers' orientation to learning and understanding of epistemic tools, (2) creating complexity maps by exploring the connection teachers make between epistemic tools (i.e., language, dialogue, and argument) and their philosophical orientations to learning (i.e., epistemology, axiology, and ontology) in their vignette responses, interviews, and written reflections; (3) comparing complexity maps across teachers from different profiles; and (4) delving into specific cases to see how these complexity maps manifest in teachers' power and agency practices in terms of language, dialogue, and argument. The following sections explain each step of the data analysis process.

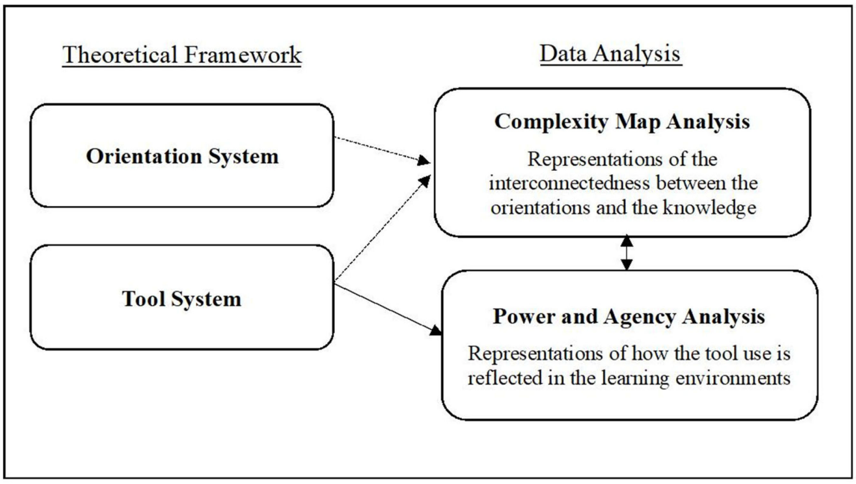


Figure 2. Alignments between the theoretical framework and data analysis.

3.3.1. Creating Two-Dimensional Teacher Profiles

We developed a method to analyze teacher profiles based on their approach to learning and understanding of epistemic tools [10]. This analysis aims to represent the growth and development of teacher AdTex. Our analysis involved examining the data collected in the second year of the project, which included vignettes, interviews, and reflections. Initially, we focused on the teachers' responses to the vignettes, using the rubric provided in the Supplementary Materials. By consolidating the responses from all four vignettes, we applied the rubric to evaluate each teacher's level of orientation towards learning and their understanding of the epistemic tools, namely language, dialogue, and argument. The rubric encompassed three criteria for each component, which were established based on a thorough review of relevant literature. Teachers who addressed three criteria in their responses were assigned a high score, those who addressed two out of the three criteria received a medium score, and those who addressed only one criterion were given a low score. As the scale progresses from low to high, teachers' understanding becomes increasingly adaptive, student-centered, and knowledge-generation-focused.

After positioning the teachers on a scale based on their vignette responses and scores, we cross-checked this scale with more open-ended data sources, such as professional development (PD) reflections and interviews. These additional data sources comprised the teachers' responses based on their actual teaching contexts, rather than a hypothetical vignette scenario. At this stage, we applied the same criteria from the same rubric to analyze interview transcripts and written reflections from PD. If this supplementary evidence confirmed the teacher's original placement on the scale, we did not alter their score. However, if the evidence contradicted or contrasted with the score derived from the vignette, we adjusted the level of orientation towards learning and understanding of epistemic tools accordingly. For instance, if a teacher demonstrated two criteria of orientation towards learning in the vignettes, they were initially scored as medium. If we discovered evidence for the third criterion in the PD reflections and interview responses that was absent in the vignette responses, we included that evidence in our analysis and adjusted the score from medium to high.

Once we scored the teachers' orientation towards learning and understanding of each epistemic tool, we generated two-dimensional profiles: (1) orientation towards learning (high, medium, and low) and (2) knowledge of epistemic tools (high, medium, and low). To determine an overall score for the knowledge of epistemic tools, we examined the scores obtained for each area (language, dialog, and argument) in the previous steps. If a teacher scored high in at least one epistemic tool and medium in the other two, we classified them as having a high level of overall knowledge of epistemic tools. For example, if a teacher received a high score in language and medium scores in both dialog and argument, they were coded as having a high level of overall knowledge of epistemic tools. If a teacher had no more than one area scored as low, we classified their overall understanding of epistemic tools as medium. However, if a teacher had two or more areas scored as low, we categorized their overall understanding of epistemic tools as low.

Out of the eleven teachers included in this study, two of them (Teresa, and Rose) exhibited a high–high profile, indicating a high orientation towards generative learning and a high understanding of epistemic tools. Additionally, three teachers (Amber, Lusia, and Julie) demonstrated a high–medium profile, two had a medium–high profile (June, and Jordan), one (Alex) had a medium–medium profile, and three others (Kennedy, Khloe, and Sophia) had a medium–low profile.

To ensure the validity and consistency of the coding process, two independent coders (graduate research assistants) conducted the profile analysis. After completing the coding separately, they compared their scores for teacher epistemic orientations and understanding of each epistemic tool. Any discrepancies in the codes were thoroughly examined, and efforts were made to reach a consensus. After several rounds of discussion, two coders reached an agreement on 97% of the codes. For the remaining codes where consensus was not reached, a third coder (another graduate research assistant) was invited to provide analysis. The scores determined by the third coder were considered final. Finally, we merged the agreed scores into a single dataset, which displayed each teacher's scores for the four constructs: (1) OL: orientations towards learning, (2) LAN: knowledge of language, (3) DIA: knowledge of dialog, and (4) ARG: knowledge of argument.

3.3.2. Creating Complexity Maps

The construction of complexity maps entailed a systematic three-step process. Initially, we carefully examined various data sources, including teacher interviews, vignettes, and reflection surveys to identify episodes that provided valuable insights into teachers' orientation to learning and their comprehension of epistemic tools. For example, a vignette asks, "Naomi completed a Science Writing Heuristic workshop last summer. She thinks her science teaching went okay this year, but she wants to use language better. Please describe to Naomi how she could think about language as she prepares. Include any steps she should take and make your thinking transparent, so she knows why those steps are important". One particular vignette was selected as an episode for further analysis due to its potential to elucidate the teacher's ability to establish connections between language and other tools, as well as language and different orientations to learning. Another example episode encompassed a reflection question that prompted teachers to complete the phrase, "This is what dialogical interaction means to me…" Teacher responses provided for this question were selected as an episode since it had a potential to reveal connections that teachers made between dialogue and other components. As a result of the data screening process, more than 20 episodes were identified for each teacher.

Following the identification of episodes, our analysis delved into the connections between epistemic tools and orientations to learning. We thoroughly examined each episode and searched for the connections forged by teachers between these crucial elements (LAN: Language, DIA: Dialogue, ARG: Argument, and OL: Orientations to Learning) by employing the rubric criteria presented in Supplementary Materials. To illustrate, in the aforementioned vignette task about language, if the teacher's response pertained to the notion of student autonomy over their language, we assigned a code, LAN-OL, indicating a connection between language and orientation to learning. This coding was derived from the rubric in Supplementary Materials, which established student control over learning as a key indicator of their learning orientation. Furthermore, if the teacher's response encompassed the implementation of whole-class and small-group discussions focused on scientific vocabulary to enhance students' understanding of the related concepts, we coded this statement as LAN-DIA which indicates a connection between language and dialogue.

This categorization aligned with one of the criteria outlined in the rubric for dialogue (see Supplementary Materials), which emphasized the utilization of both private and public dialogue spaces during discussions. The same procedure consistently applied, ensuring a comprehensive analysis of all episodes until completion for all teachers. See Table 2 for example connections between OL, language, dialogue, and argument.

Table 2. Example connections between OL, Language, Dialogue, and Argument.

Connections	Example Statements
OL-LAN	"Summary writing is a great tool to use when trying to see a student's understanding of a concept. It allows students a chance to really share what they have learned and not just what they can memorize for a test" (Amber, Reflection Data)
OL-DIA	"Then, ask students to pose questions. These student questions will guide the unit of study. You will also have a chance to support classroom climate by ensuring every student has a voice" (Rose, Vignette Data)
OL-ARG	"Try to stay out of the negotiation process as much as possible to allow for student engagement" (Teresa, Vignette Data)
LAN-DIA	"Dialogical interaction is the dialog between student–teacher or student–student. It can include written or spoken language" (Lusia, Reflection Data)
LAN-ARG	"I can see where it is best to allow students to negotiate their own interpretation of language based on their own resources" (June, Reflection Data)
DIA-ARG	"Everyone should be able to have a chance to speak without being interrupted. Kevin may have to work on how students should interact in small-groups during conversations. Students may not know how to carry on a discussion so he may have to explicitly explain or practice this. Perhaps Kevin could call on a group to role play different situations, like two students agree on something and one disagrees. How could the conversation happen to respect each other and still get to share their viewpoints. And lastly, Kevin should make sure to explain what argument means and let the students know we argue ideas and not people" (Jordan, Vignette Data)

After identifying connections between language, dialogue, argument, and orientation to learning, our attention turned to examining the specific relationships between each philosophical orientation to learning (EPS: epistemological orientation, ONT: ontological orientation, and AXI: axiological orientation) and epistemic tools (LAN, DIA, and ARG). To accomplish this, we employed an additional rubric. This rubric outlined three criteria for each philosophical orientation to learning. For instance, if a teacher discussed the significance of dialogue in facilitating student learning, that statement was coded as a connection between AXI and dialogue. For more examples and an overview of the rubric, please refer to Table 3.

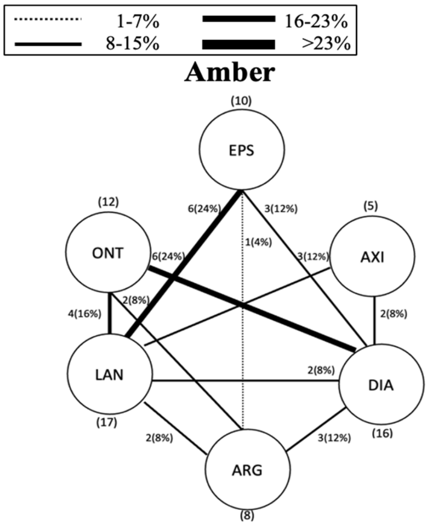
Finally, we created the maps to show the complexity of connections by using the total number of connections between each component. To represent the degree of connection between two components, we divided the total number of connections between these components by the total number of episodes, since the maximum number of connections we can get for the two components could be equal to the number of episodes. For instance, in the case of Amber, who made connections between LAN and EPS in 6 out of the 25 episodes, we calculated the percentage of connections between LAN and EPS by dividing 6 by 25. Employing the same calculation for all potential connections, we obtained a set of percentages as illustrated in Table 4. These percentages were then used to map the relationships, with the thickness of the lines on the map reflecting the frequency of the connections. The complexity maps visually represent the connections based on their frequencies. As the frequency of connections increases, the lines representing those connections are shown with greater thickness on the map.

Table 3. Criteria for philosophical orientations to learning and example connection coding.

Epistemology (EPS)	**An Example Connection**
• A teacher would believe a rapidly changing system of knowledge (Knowledge is tentative and constructed by multiple authorities) [45] [Conditions of uncertainty] • A teacher would emphasize a dynamic (student-centered) curriculum. She would highlight active participation of the learners [45] [Sources of knowledge] • A teacher believes that the learner acquires subjective knowledge from direct experience (ability to creating the learner's own mental schemes by connecting existing and new knowledge) [86] [Acquisition of knowledge]	*An example connection between argument and epistemology:* "Step out of the way and let kids share their thinking. Work to not give answers, but to continue to probe with questions. After students negotiate as a whole class, allow them more individual time to connect what they just learned to what they started out knowing" (Lusia, Vignette Data)
Axiology (AXI)	**An Example Connection**
• A teacher believes that the learner can construct knowledge and relate their learning with other concepts by using multiple forms of language [69] [Value of language] • A teacher believes that student-centered dialogue is a valuable knowledge generation tool that helps students to make meaning of concepts and relate their learning with other concepts [70] [Value of dialogue] • A teacher believes that immersive use of argument is an essential knowledge generation tool which helps students to construct knowledge and to make connections with the big idea [84] [Value of argument]	*An example connection between dialogue and axiology:* "Dialogs should be a part of the entire day because it is an integral part of student learning. Dialogue means for learning and so it is not limited to science class only or Fun Fridays" (Rose, Vignette Data)
Ontology (ONT)	**An Example Connection**
• A teacher would assume "different people have different realities and that these realities are constructed in social settings" [45] [Sociocultural interaction of learning] • A teacher would assume that students have the ability to learn and have control over their own learning in the classroom. A teacher would assume that students author their own learning in the classroom (learners conduct the inquiry and collect evidence on their own) [74] [Control/Authority of learning] • A teacher would assume her role in the classroom as a collaborator, a co-participant, and a facilitator of learning who works to meet the individual needs of students [57] [Role of teachers in the classroom]	*An example connection between language and ontology:* "She needs to make this use of language as fluent as possible. She needs to create the classroom environment that fosters the free exchange of language in its many forms. She also needs to give control of the language to the students. How and the steps to get there are something that I am working on" (June, Vignette Data)

To ensure the reliability and validity of the analysis procedure, a graduate student and a postdoctoral scholar worked collaboratively. They first randomly identified two teachers' data to be coded. Then, they independently coded the connections between each component using the rubric. Subsequently, they met to reconcile any discrepancies and identify similarities in their coding. Following a second round of meetings, they reached a consensus on the majority of the connections that were coded. Thereafter, one of them proceeded to code the remaining teachers' data, ensuring consistency in the analytical approach.

Table 4. An example of complexity map and percentage calculations.

Complexity Map	Calculations
	Total number of episodes: 25 EPS-LAN: (6/25)*100 = 24% EPS-DIA: (3/25)*100 = 12% EPS-ARG: (1/25)*100 = 4% ONT-LAN: (4/25)*100 = 16% ONT-DIA: (6/25)*100 = 24% ONT-ARG: (2/25)*100 = 8% AXI-LAN: (3/25)*100 = 12% AXI-DIA: (2/25)*100 = 8% AXI-ARG: No connections LAN-DIA: (2/25)*100 = 8% LAN-ARG: (2/25)*100 = 8% DIA-ARG: (3/25)*100 = 12%

3.3.3. Comparison of Complexity Maps across Different Teacher Profiles

At this stage, we combined complexity maps from teachers based on their two-dimensional profiles, as depicted in Figures 3–6. Subsequently, we conducted a detailed analysis of the cases to identify shared and unique patterns among the profiles in terms of the complexity of the connections they established.

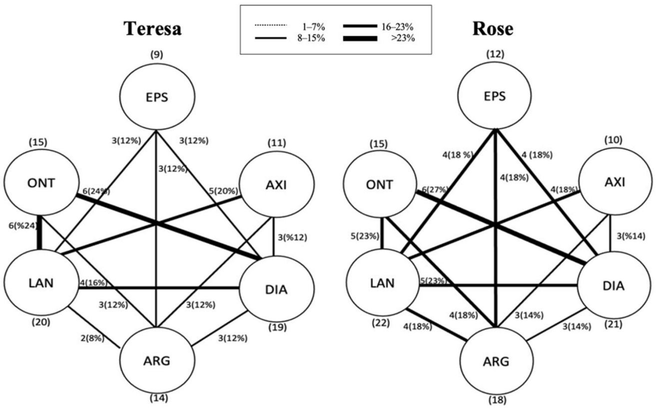


Figure 3. High–high profile teachers' complexity maps.

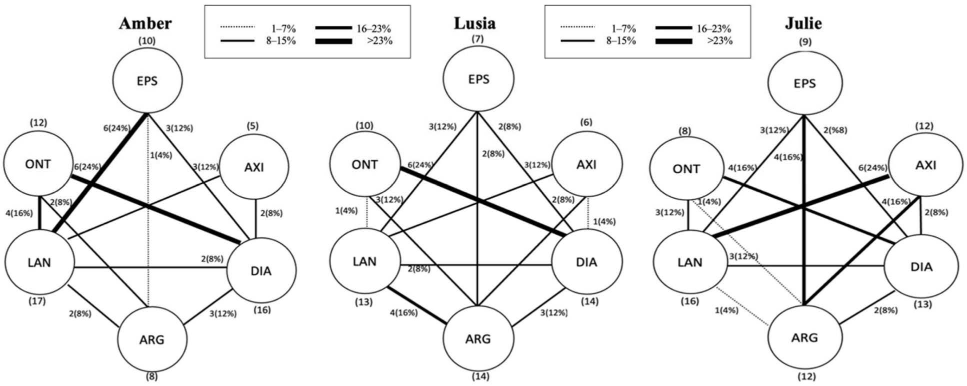


Figure 4. High–medium profile teachers' complexity maps.

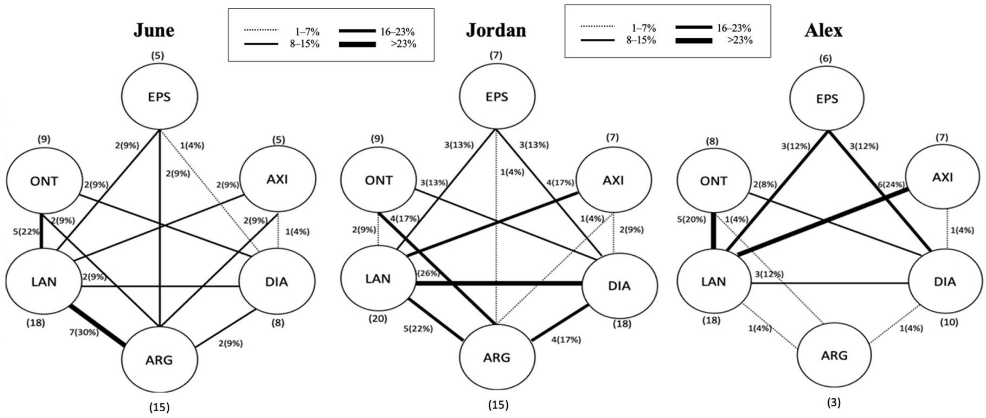


Figure 5. Medium-high and medium–medium profile teachers' complexity maps.

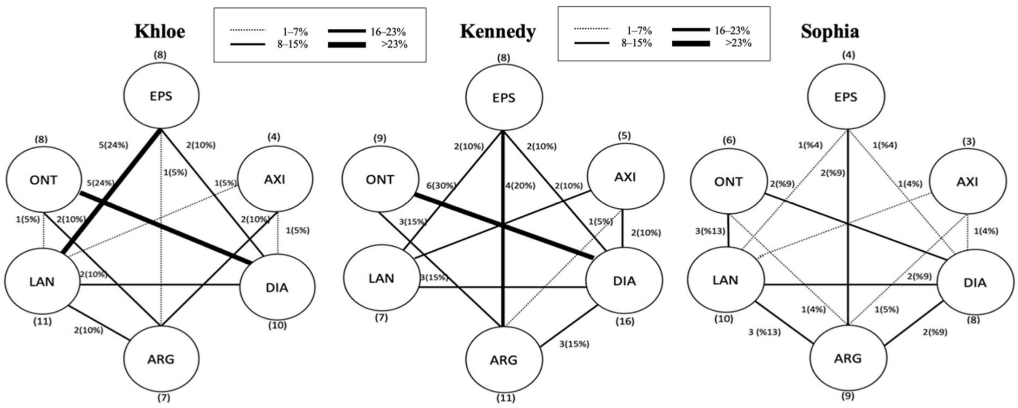


Figure 6. Medium-low profile teachers' complexity maps.

3.3.4. Power and Agency Analysis

In our second main analysis concerning the utilization of epistemic tools in learning environments (refer to Figure 2), we conducted a detailed examination of the speech and listening characteristics of five participating teachers (Rose, Teresa, Alex, Amber, and June) by reviewing their classroom videotapes from TP4. Our focus was on how language, dialogue, and argument are framed and utilized in practical classroom settings. The classroom videotapes were recorded during scheduled field observations with each teacher. The average duration of the five videotapes was approximately 34 min, ranging from 16 to 46 min in length.

To analyze the classroom videotapes, we employed a priori codes with a 5-point Likert scale (refer to Table 5). The first eight items concerning language and dialogue were adapted from author [87], while the additional items were developed based on a comprehensive literature review focused on argumentation in the classroom. Initially, we divided each classroom video into two-minute segments and applied dichotomous coding based on the power and agency rubric. For instance, if a teacher used technical vocabulary (such as "chlorophyll") in a given two-minute segment, they were assigned a score of 1 for the Tvocab code. If no technical vocabulary was used in that particular segment, a score of zero was assigned. After coding all segments in each teacher's videotapes, we calculated the percentage of scores for each power and agency code. These percentages were then rounded up to align with the 5-point Likert scale (1. Never, 2. Infrequently, 3. Sometimes, 4. Frequently, and 5. Always).

To ensure inter-rater reliability, a second coder was trained on the power and agency rubric and conducted a pilot coding using a sample classroom videotape. Discrepancies between the two coders were discussed until a consensus was reached. Subsequently, four classroom videotapes from participant teachers were randomly selected and independently analyzed. The weighted kappa coefficient for the total scores between the two raters was determined to be 0.81, indicating a strong level of agreement [88]. Finally, the remaining three teachers' videotapes were analyzed by the first coder.

Table 5. Teacher speech and listening characteristics.

Codes		A Score of 1 (toward Formality)	A Score of 5 (toward Informality)	Justification of the Code
Language	Trelax	Body language includes stiff posture and little movement. Absence of laughter or pronounced facial expressions.	Body language includes fluid posture and frequent movement. May laugh other emotive sounds. Facial expressions tend to be pronounced.	Non-authoritarian body language can help students feel less anxious about being corrected by authority figures [87].
	Tvocab	Nearly all speech utterances use discipline-specific vocabulary words in the science classroom.	No use of discipline-specific vocabulary words in the science classroom, such as igneous, solute, etc.	Vocabulary choices reflect the speaker's power expression and their perception of their listeners' relative power [87].
	Tslow	Teacher speaks artificially slowly during science, relative to outside interactions.	Speech maintains normal to quick conversational tempo during science, relative to outside interactions.	Slow tempo speech indicates linguistic formality [89].
	Tlow	Tone of the teacher's voice becomes artificially low during science, relative to outside interactions.	Tone of the teacher's voice remains normal to artificially high during science, relative to outside interactions.	Low-tone speech indicates linguistic formality [89].
Dialogue	Tfluid	All student speech is preceded by formal request, such as hand-raising or being called upon.	All members of the classroom speak freely via natural conversational turns, interjection, or interruption.	To promote meaningful dialogue, it is crucial that every individual in the classroom has equal access and power, enabling them to freely express their ideas [87].
	Tsumm	Teacher does not summarize students' speech before adding their own input to the dialog.	Teacher nearly always summarizes students' conversational contributions before adding their own input to the dialog.	Speech summarization assists students in internalizing and contextualizing the thoughts of others [87].
	Tss	Teacher does not promote extended sequences of student–student talk.	Teacher consistently promotes extended sequences of student–student talk.	Conversational turns of student–student talk can provide evidence for meaningful dialogue in the classroom [90].
	Tfreq	Conversational turns in the classroom are rare. Most speech consists of teacher lecturing.	Conversational turns in the classroom are very common. Teacher does not lecture. Most speech is dialogical.	The frequency of dialogue interchange can serve as a measure of the quality of the dialog [87].
Argument	Tquest	No use of open-ended questioning to promote student reasoning.	Teacher consistently uses open-ended questioning to promote student reasoning.	Teachers employ questioning as a primary approach to foster generative learning, as it prompts students to generate ideas through reasoning [91,92]
	Targ	Teacher does not encourage students to critique, support, and defend their ideas in an argumentation.	Teacher consistently encourages students to critique, support, and defend their ideas in an argumentation.	Engaging in argumentative discourse offers students a meaningful opportunity to assert their agency and demonstrate their power within the classroom [87].
	Tcomm	Teacher does not participate in learning community during negotiation (expresses "I" or "you" rather than "we").	Teacher consistently positions themselves as a part of learning community during negotiation (expresses "we" rather than "I" or "you").	It is crucial for teachers to shift their focus towards considering students as subjects rather than objects, thereby creating an environment where students can express their power [61].
	Tprior	Teacher does not integrate what students have learned previously into the concepts discussed.	Teacher consistently integrates what students have learned previously into the concepts discussed.	Learning can be defined as the process of generating knowledge that occurs when learners establish abstract and distinct connections between their prior experiences [93].

4. Results

4.1. Patterns in Complexity Maps among Teachers from Different Profiles

Figures 3–6 illustrates significant variations in the complexity maps among different profile teachers.

Moving from low-profile to high-profile teachers, the relationships between philosophical orientations and epistemic tools became more complex. Specifically, high-profile teachers established a greater number of connections between epistemic tools and philosophical orientations to learning. For instance, Rose and Teresa, who exhibited a high inclination towards generative learning and possessed a high understanding of epistemic tools, established a total of 98 and 88 connections, respectively. On the contrary, Khloe, Kennedy, and Sophia, who displayed a moderate orientation towards learning and showed a low understanding of comprehension of epistemic tools, established fewer connections, with totals of 48, 56, and 40 connections, respectively.

A notable disparity emerges in the connections established by high-profile teachers between epistemic tools and axiology. In other words, these teachers emphasize the value of these tools in enhancing student learning more frequently compared to low-profile teachers. For example, Rose and Teresa highlight the significance of language in student learning on multiple occasions. In one vignette response, Rose suggests that "Language is essential to learning. Language is how we build meaning and express it… Naomi will want to provide students with multiple opportunities to use language through listening, speaking, writing, and reading". Similarly, Teresa underscores the value of language by stating, "Think of language as any communication your students use throughout learning. Students use language when writing and speaking". (Vignette Data).

High-profile teachers have complexity maps that show a strong interconnectedness among all elements. This distinguishes them from their medium- and low-profile counterparts whose maps show weaker or fewer connections in certain areas. High-profile teachers effectively link all components, unlike medium- and low-profile teachers, who either miss some connections or exhibit weaker links between philosophical orientations and epistemic tools.

Rose and Teresa, the high-profile teachers, establish all possible connections between the components. They ensure that no components are left unconnected to others. Moreover, they establish stronger connections between ONT and DIA, as well as ONT and LAN, emphasizing their orientations toward student-controlled use of dialogue and language. For instance, Teresa promotes the normalization of dialogic interactions in the classroom, suggesting, "Make it something students know is going to happen each and every day. Try taking yourself out of the equation to allow students to have more of a voice" (Vignette Data).

Medium-profile teachers, who demonstrated a moderate level of orientation to generative learning or understanding of epistemic tools, or both, also displayed stronger connections between certain philosophical orientations and epistemic tools. However, in comparison to high-profile teachers, their maps appeared unbalanced, featuring weaker connections between certain components. In most cases, the epistemic tool that connected less with philosophical orientations and other epistemic tools was the argument. For instance, Amber established weaker connections between AXI and ARG, and there was one instance where she connected ARG with EPS. Similarly, Jordan and Alex connected the ARG component less frequently with philosophical orientations.

Similarly, low-profile teachers showed relatively loose maps with weaker connections or no connections between some components. For instance, Khloe's map did not show connections between ARG and DIA, and the connections between LAN and ONT, as well as EPS and ARG, were weak. Similarly, Kennedy lacked connections between LAN and ARG. Sophia also demonstrated weaker connections between various components, such as ONT-ARG, EPS-DIA, and EPS-LAN.

In general, although every teacher has their own unique map structure, the maps of high-profile teachers exhibited more interconnectedness between their philosophical orientations to learning and the epistemic tools.

4.2. The Relationship between Complexity Maps and Visible Utilization of Epistemic Tools

In order to understand more clearly about how the interplays seen in the complexity maps are reflected in the learning environments, we conducted an analysis of classroom videos and assessed the level of power and agency in terms of language, dialogue, and argumentation (see Figures 7–9 for the comparison of complexity maps and power and agency analysis). Due to the impact of the COVID-19 pandemic, we encountered limitations in accessing all eleven classrooms of the teachers initially under investigation. Nonetheless, we managed to gather valuable classroom data from five teachers, offering comprehensive insights into how their complexity maps manifest in their teaching practices. Because of space limitations, we present a comprehensive description of three selected cases based on their profiles.

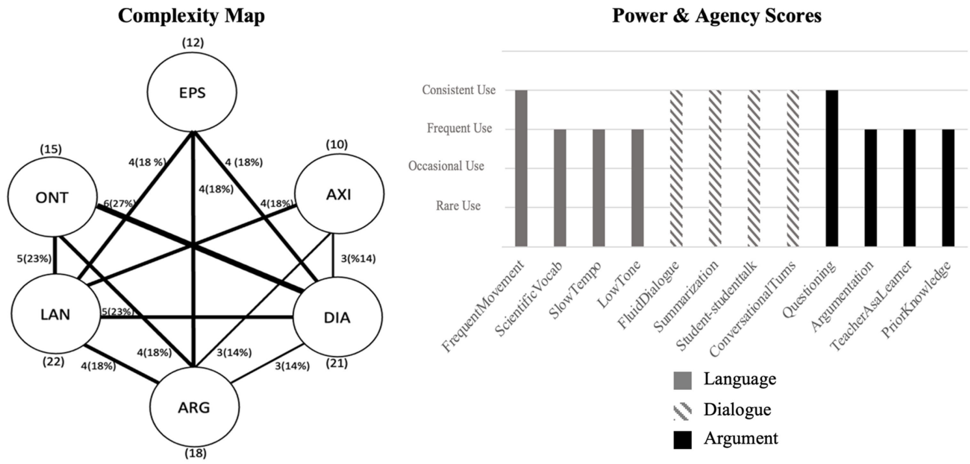


Figure 7. Complexity map and power and agency scores for Rose.

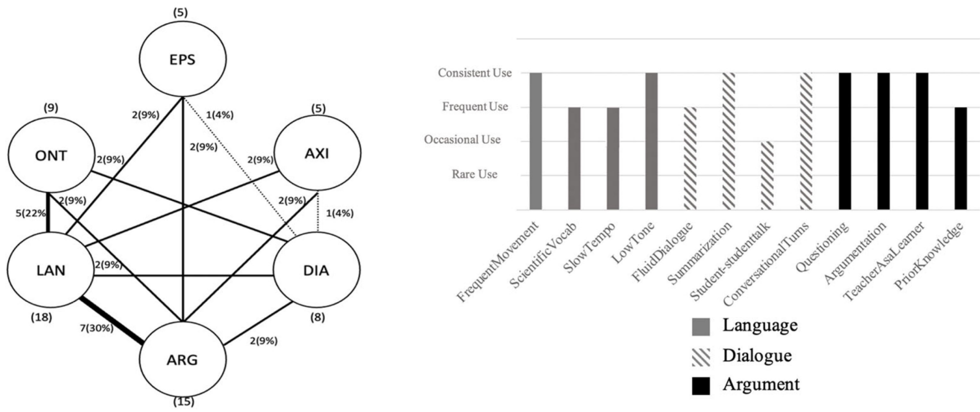


Figure 8. Complexity map and power and agency scores for June.

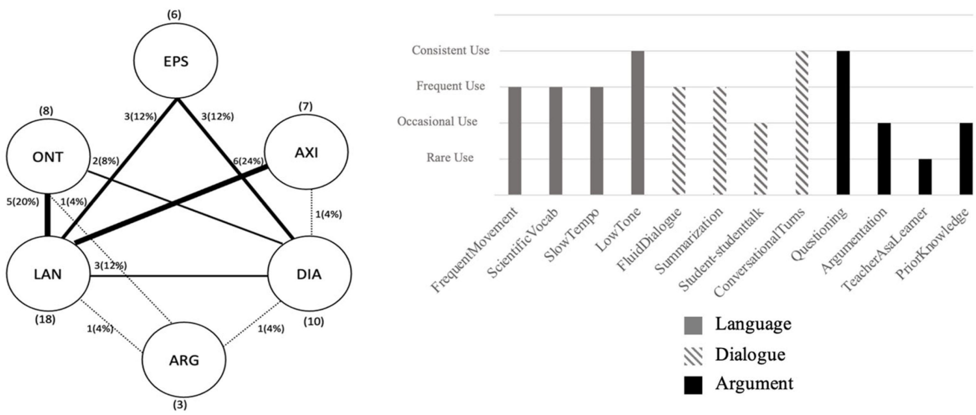


Figure 9. Complexity map and power and agency scores for Alex.

4.2.1. Rose's Case

Rose was a fifth-grade teacher who taught all subjects in a public school. She was one of the high-profile teachers who showed a profound understanding of epistemic tools and exhibited strong orientation towards generative learning. During our observation of her classroom amidst the COVID-19 pandemic, she and her students talked about factors affecting brightness of the star. There was a big idea posted on the board says, "Brightness of the stars depends on many factors", accompanied by student-generated questions related to this big idea. Throughout the observed lesson, Rose and her students tried to answer one of those questions which was "How does the location of a star affect brightness?". In the subsequent sections, we delve into her language usage, dialogue practices, and the reflection of her complexity map in her teaching approach.

Language: Based on power and agency analysis, she showed frequent use of language in her classroom. During the observed lesson, she frequently moved all over the classroom and provided guidance to individual students as needed. Her tone of voice remained normal, although she occasionally heightened it to express enthusiasm for the students' ideas. Her facial expressions convey appreciation, surprise, and genuine interest in the students' responses. Both Rose and her students frequently employed scientific vocabulary when discussing the driving question. For instance, when exploring the factors that could impact star brightness, students provided diverse answers, including size, location, age, color, temperature, and creation.

Dialogue: She was scored as 4 out of 5 in terms of student power and agency over the classroom dialogue. Dialogue played a prominent role in her classroom, with students engaging in conversations of varying group sizes. For instance, Rose prompted her students to formulate claims within their groups to explain the relationship between star brightness and location. She visited each group's table, actively engaging with every student, including those who initially appeared disinterested. Rose posed follow-up questions to better comprehend the reasoning behind their answers and to clarify their responses. She expressed gratitude for their collaborative efforts, stating, "Before we share, I was going to compliment you guys because everyone was taking turn and talk. I really appreciate that each member of your team was contributing the discussion". She constantly tried to motivate students to share their ideas by saying "Keep thinking", "Tell us more", "That is a great question!", and "That is very interesting". She always seemed interested when a student talked and summarized what students said after they talked. The classroom environment predominantly featured dialogical discourse rather than teacher-centered lectures. Student ideas and contributions served as guiding forces in shaping the learning experiences. For instance, in their exploration of star brightness, Rose gathered all students on the carpet at the front of the classroom. They started by examining the effect of distance on star brightness, employing two flashlights to test their hypothesis. While one student conducted the experiment, others observed and offered insights. When a student suggested that one flashlight was positioned near a window, potentially impacting its brightness, they collectively decided to adjust its placement. Another student hypothesized that the different flashlights used might affect the brightness, prompting Rose to suggest trying various flashlights. Thus, the investigations were guided by the contributions of both the students and the teacher.

Argument: Rose frequently employed open-ended questions to foster students' reasoning abilities. However, it was primarily the teacher who initiated critiques and explanations, and naturally occurring student–student negotiations were not common. There were also instances where Rose conveyed mixed messages regarding her positioning of herself and the students within the learning community. An illustrative dialogue between Rose and her students exemplifies this:

> ***Teacher:*** *What if a question is testable?*
>
> ***Student:*** *You can make an experiment.*
>
> ***Teacher:*** *That is exactly what I hope to get into today. What I gonna do, what we gonna do, if you are all in, if you want to try an experiment today. What we are going to do, today we are going to test the question we came up.*

In this dialogue, it becomes apparent that Rose attempted to transition from using "I" language to employing "we" language when explaining their collective endeavors in the classroom.

Overall, Rose's practices demonstrated a greater emphasis on supporting student agency through her language and argumentation practices, while her dialogue practices exhibited even stronger elements of promoting student empowerment. Power and agency analysis showed frequent use of language, consistent use of dialogue, and frequent use of argument. The results of the power and agency analysis aligned with the findings concerning the teachers' complexity maps (Figure 7). Rose forged deeper connections between dialogue and ONT, delving further into the sociocultural dynamics of learning through dialogue, recognizing students as authoritative contributors guiding the discourse, and assuming the role of a collaborator striving to meet individual student needs. For example, in her vignette response at TP4, she wrote, *"ask students to pose questions. These student questions will guide the unit of study. You will also have a chance to support classroom climate by ensuring every student has a voice. Students will participate in dialogue to negotiate guiding questions for science learning. It important to remind students that because we negotiate ideas and not people, and they are encourage to engage in the dialogue with their peers to steer their learning"*.

4.2.2. June's Case

June was a departmentalized teacher who teaches science in a public elementary school. She was one of the teachers who showed moderate orientation to generative learning yet strong understanding of epistemic tools. During her classroom observation, she and her students held negotiations around gravity concepts and did some experiments to research their guiding questions. She started her lesson by introducing the big idea written on the board which was "Gravity pulls the objects down". In the subsequent sections, we described her language usage, dialogue, and argument practices in more detail.

Language: Most of the time in her classroom session, June was standing in front of the board, asking questions and writing down the students' ideas and questions. Rather than speaking at a low and monotone speed, she was making various intonations by adding melody to her voice. She showed her interest in student ideas and admiration for the ideas they came up with. For example, when they talk about how they test the idea of gravity pulling the objects down, a student came up with a question of whether gravity affects all the objects equally. June said " Wo Wo Wo! Oh my God! This is a great question" and she immediately wrote the question to the board for further discussion. Both she and the students brought up different scientific vocabulary including gravity, force, weight, mass, and speed.

Dialogue: Her class was mostly dialogical with a lot of teacher and student questioning. She usually asked challenging questions and nearly always summarized students' answers to add their input to the dialog. However, the dialogues were mostly between her and the students, rather than peer and group discussions. In addition, student speech was preceded by formal requests, such as hand-raising or being called upon. She wanted students to work on their experiments individually and to come up with some further experiment ideas individually to test if bigger objects fall slower or faster. The only formal peer interaction happened after that activity. She gave students two minutes to find someone to share their experiment plans.

Argument: She mostly used open-ended questions to promote student reasoning such as "What affects the speed of falling?", and "How weight can affect the speed of falling?". She employed question–claim–design and evidence cycle frequently. She wanted students to design a helicopter header with the materials she gave to students to test what affects the speed of its falling. She asked students what they can change to change the rate of its fall. After one student came up with the idea of expanding the wings out, she provided more materials to test his idea. Another student suggested increasing its weight, and she gave extra clips to add to the helicopter so the student can test his idea. When another student mentioned that air can affect the speed of a falling object, she asked about how they can test the effect of air. She also positioned herself as a part of the learning community by mostly using the "we" pronoun. For example, she said, " Do we still agree that if something is bigger, it is going to fall slower? Ohh, We have to do that. We have to figure that out". In addition, she tried to integrate what students have learned previously into the concepts discussed. For example, when a student talked about how mass can affect a falling object, she tried to make sure that students know the difference between weight and mass. She asked how they defined those concepts before and how they are different.

Overall, June's practices demonstrated a greater emphasis on negotiation around scientific vocabulary and testing ideas, while her dialogue practices were more teacher-centered. Her power and agency analysis showed frequent use of vocabulary, frequent use of dialogue with occasional use of student–student talks, and consistent use of argument. The findings from the power and agency analysis were consistent with the results obtained from the teachers' complexity maps (Figure 8). Notably, her map revealed a strong connection between language and argument, highlighting the importance of negotiating a shared understanding of scientific vocabulary across multiple episodes. In one of her reflections, she wrote " I love to negotiate the use and definitions of key concept terms". However, her map also indicated weaker connections between DIA and AXI, as well as DIA and EPS, which aligns with her classroom dialogue practices. It suggests that she may not have fully recognized the value of student-controlled dialogue in their learning, which could limit her ability to fully benefit from student–student interactions.

4.2.3. Alex's Case

Alex was a fourth-grade teacher who taught in a Midwestern state of the USA. He was one of the teachers who scored as a medium in terms of both his orientation to generative learning and his understanding of epistemic tools. During our observation of his classroom, the topic of discussion was ecosystems. His language, dialogue, and argument practices are described below:

Language: Alex encouraged his students to establish connections between the concepts displayed on the board, encompassing entities such as dolphins, coral, water, boats, garbage, fish, and animals. The students took turns approaching the board and drew lines to establish connections they perceived to be relevant. Neither Alex nor the students engaged in verbal discussions pertaining to their individual connections until all students had completed this exercise. Subsequently, Alex invited students to articulate the rationale behind their chosen associations. Alex maintained a stationary position near the board, posing the same set of questions to each student fastly without too much elaboration.

Dialogue: In Alex's classroom, although every student was afforded the opportunity to express their thoughts, interactions between students themselves were infrequent. The predominant dynamic consisted of the teacher posing questions, and students responding once called upon. The class discussions revolved around four central inquiries: "Which items did they connect?", "What prompted their connections?", "Among the listed items on the board, what is classified as living and nonliving?", and "What are their reasons for considering certain items as living or nonliving?". Each student received the same set of questions from Alex, and their responses were swiftly provided without extensive elaboration from either the teacher or their peers.

Argument: Alex occasionally employed open-ended questions to gain insight into students' reasoning behind their ideas. For instance, when one student made a connection between starfish and rocks, Alex inquired about the student's rationale. In response, the student explained that starfish stand on rocks, prompting Alex to delve deeper by asking how the student acquired this knowledge. Similarly, when another student asserted that coral is alive, Alex engaged the entire class by requesting a show of hands from those who shared this belief. He then proceeded to ask a couple of students to expand upon their reasons for considering coral as a living organism. While Alex encouraged students to articulate their reasoning, it was not a frequent and natural practice. He did not create opportunities for students to expand upon or critique each other's ideas. Furthermore, his role in the classroom predominantly assumed that of an authoritative figure who posed questions, rather than positioning himself as an integral part of the learning community.

In general, Alex's classroom teaching revealed a greater focus on soliciting individual students' ideas and establishing scientific vocabulary. However, the majority of the dialogue relied on the teacher's initiation. The analysis of power and agency indicated frequent use of language and occasional utilization of student–student interactions and arguments. These findings aligned with the outcomes derived from the teachers' complexity maps

(Figure 9). Particularly strong connections were observed between LAN and ONT, as well as LAN and AXI, which were evident in Alex's practice of defining scientific vocabulary to enhance comprehension of the subject matter. Conversely, weak or nonexistent connections were observed between argument and philosophical orientations, as well as argument and other tools in Alex's map. It appears that Alex may not fully grasp how argument can serve as an epistemic tool to support student learning, nor how it can integrate with other epistemic tools. The lack of connections between these elements may explain why Alex only occasionally employs argument rather than developing a meaningful, regular practice of it.

5. Discussion

Our study represents a pivotal phase in our sustained efforts to unravel the intricate dynamics of teacher development for AdTex. Guided by the embrace of a complexity framework (e.g., [18,94]), our journey into AdTex development, despite the inherent challenges, offers considerable promise. It has prompted us to formulate new inquiries, shift our investigative focus towards previously unexplored domains for explanations, and adopt innovative perspectives to enhance our understanding of teacher development. Rooted in our prior research, which underscored the importance of epistemic orientations and knowledge of epistemic tools, our current findings spotlight salient patterns in the intricacy of teacher development. These patterns reveal a variability yet coherence among different teacher profiles.

Foremost, our results echo the sentiment that, to grasp the intricacy of teaching, one must move past mere knowledge accumulation [15]. It requires a profound, interconnected comprehension shaped by the synergy of multiple facets [95]. Notably, high-profile teachers like Rose and Teresa showcased a pronounced orientation towards generative learning and a comprehensive grasp of epistemic tools. The complexity maps reflect this comprehension, illustrating the strong and intricate connections between the philosophical orientation system and knowledge of epistemic tool system, thereby establishing their solid foundations in adaptive expertise.

Digging deeper, our analysis underscores the importance of acknowledging the inherent interconnectedness of elements such as dialogue, language, or argumentation. These cannot be examined in isolation, as their mutual influences compound the overall complexity. This interconnectedness within a system is depicted in high-profile teachers' complexity maps, demonstrating their comprehensive understanding of adaptive teaching for knowledge generation. These insights should inform the design of teacher development programs, prompting a comprehensive approach that considers the interaction among different components of adaptive teaching for knowledge generation.

Shifting the lens, our study accentuates the crucial impact of philosophical orientations—specifically, ontology and axiology—on adaptive instructional practices. While epistemology has traditionally been the focal point in science education studies, ontology and axiology have somewhat been sidelined [49]. However, our complexity maps demonstrate a notable trend: teachers who successfully integrated learning tools with their ontological perspectives were notably adept at utilizing these tools in teaching. This suggests that a teacher's views on the nature of reality, their ontological beliefs, profoundly inform their understanding of student learning and the ways they apply learning tools to foster student-centric environments. Similarly, axiology, which pertains to values and ethics, molds a teacher's approach to teaching and their relationships with students [61]. We observed that, when there was a disconnect between a learning tool and axiology, that tool was often excluded from classroom practices. Recognizing the significance of ontology and axiology is therefore essential to fully understand adaptive teacher development. By reflecting on these philosophical foundations, teachers can gain clarity on their pedagogical choices, enabling them to tailor their methods to align with their core beliefs and the dynamic learning needs of students.

A central contribution of our study is the development of a comprehensive framework that defines various belief systems, referred to as orientation systems, and the foundational knowledge necessary to nurture generative learning environments. Research, such as the studies by Lee et al. [96] and Stipek and Byler [97], has indicated possible inconsistencies between beliefs and practices. However, we firmly assert the pivotal role of beliefs as drivers of actions. It is insufficient to restrict discussions solely to the congruence between beliefs and practices. A more constructive approach involves examining the intricate interplay between beliefs, knowledge bases, and teaching practices. It is crucial to consider the depth at which these components are evaluated, a sentiment underscored by works like those of Sahin et al. [98], Wilcox-Herzog [99], and Fives and Buhls [100]. The interplay between beliefs, knowledge, and practices can shift based on the predominant subsystems a teacher aligns with, particularly when adopting knowledge-generation methods in science classrooms aligned with the NGSS. Recognizing this, there has been a growing demand for a holistic framework that clearly defines belief and knowledge systems. In light of this, we believe our framework serves as a foundational step, promising to enrich future research endeavors in this area.

Another significant contribution of our study to the academic landscape is the introduction of complexity maps. These maps present an innovative framework to delve into the nuanced and often understated aspects of teacher development for adaptive teaching. Drawing on evidence from Anthony et al. [101] and Timperley [36] and the mapping approach introduced by Park and Chen [102], we used these maps to shed light on the intricate relationships among various elements within subsystems. We envision this framework as a dynamic tool to monitor a teacher's evolution in AdTex development. While each teacher embarks on their distinct journey towards AdTex, researchers can construct a series of maps over different periods. This allows both researchers and professional development (PD) leaders to oversee progress and recalibrate interventions if necessary. Beyond research, these maps can aid teachers in self-reflection, helping them pinpoint areas for growth and strategize enhancements. This can then guide professional development initiatives, ensuring they are attuned to the needs of teachers. Rather than being a rigid assessment instrument, the complexity map is designed to be a springboard for ongoing learning and refinement in teaching methods.

While this research has provided valuable insights into teacher development for adaptive teaching using complexity maps, it is not without its limitations, primarily associated with the multiple case study design. First, the sample size of this study was relatively small, and the teachers were selected from a specific educational context. This limits the generalizability of our findings across broader contexts. Future research should include a larger and more diverse sample of teachers, involving various educational settings, to further validate and enrich our understanding of complexity maps. Second, the case study design of this research, though ideal for exploring complex phenomena in real-world contexts, can limit the ability to draw definitive conclusions due to the influence of confounding variables. The relationship between complexity maps and various factors such as teachers' experience, educational backgrounds, and teaching contexts may have been influenced by other uncontrolled factors inherent in the teaching environments. Furthermore, this study focused primarily on epistemic tools and philosophical orientations, while other significant aspects of teacher development for adaptive teaching may have been overlooked. For a more comprehensive understanding, future research could investigate other aspects of teacher development such as teacher beliefs, attitudes, and classroom management skills.

In-depth studies exploring the relationship between complexity maps and a broader array of factors, such as teachers' motivations for learning, PD experiences, educational backgrounds, and teaching contexts, could provide additional insights into the multifaceted nature of teacher development for adaptive teaching. Such studies would allow us to see how different contexts and teacher characteristics interact with their philosophical orientations and knowledge of epistemic tools to influence their approach to adaptive teaching. This can further expand our understanding of the complexity of teacher development and provide more nuanced guidance for teacher training and professional development programs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci14040415/s1, Table S1: Rubric to Create Two-dimensional Profiles.

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