



Beyond Asynchronous and Synchronous: Bichronous Online STEM Professional Development in Bioinformatics for High School Science Teachers

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Abstract: Since connecting individual sensemaking with collective inquiry under time constraints is critical for teacher learning, online teacher professional development is essential for supporting STEM teachers in emerging interdisciplinary fields such as bioinformatics. Yet, existing programs typically deliver content through either asynchronous or synchronous modalities in isolation, and the absence of empirically grounded frameworks for K-12 STEM teacher professional development leaves unclear how design decisions across modalities shape collaborative teacher learning. This study examines how a bichronous model, combining asynchronous and synchronous modalities, mediates collaborative teacher learning. Using integrated Massive Open Online Course and video-conferencing platforms as learning environments, nine high school science teachers participated in a four-week online summer professional development course addressing teaching bioinformatics. Through analysis of 1,363 asynchronous forum posts and 205 minutes of synchronous sessions, findings revealed how teachers fluidly moved between self-paced exploration in threaded discussions and real-time problem-solving in video meetings. The platform design enabled two complementary pathways: asynchronous forums supported persistent knowledge building through archived threads and peer resource sharing, while synchronous tools facilitated immediate collective sensemaking and expert modeling. This study demonstrates how strategically integrated online modalities create a unified learning ecology that transcends traditional synchronous-asynchronous boundaries. Findings offer design implications for technology-mediated teacher collaboration in emerging STEM domains.

Keywords: Asynchronous learning, Bichronous learning, High school STEM education, Online teacher professional development, Synchronous learning.

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Introduction

Teacher professional learning is a gradual process requiring sustained, iterative cycles of reflection and practice within professional learning communities (PLC) (Darling-Hammond et al., 2017; Desimone & Garet, 2015; Haug & Mork, 2021). Yet, time constraints remain a primary barrier to teachers' participation and growth in professional development (PD), particularly when PD must compete with daily instructional demands (Creagh et al., 2025; Haug & Mork, 2021; Tuohilampi et al., 2024). These constraints are further magnified in interdisciplinary STEM contexts, where teachers must simultaneously develop competence in unfamiliar, complex content knowledge (CK) and confidence in pedagogical content knowledge (PCK) across multiple domains while integrating real-world science practices with authentic tools and data into their classrooms (Huang et al., 2022; Mohamad Hasim et al., 2022; Rosen & Vasconcelos, 2025; Yoon et al., 2025).

Online teacher professional development (oTPD) is often recognized as a solution to the challenge because it offers teachers with flexible access and expanded opportunities to learn with peers and experts (Bragg et al., 2021; Jin et al., 2024; Lay et al., 2020; Meyer et al., 2023; Moore et al., 2024; Stavermann, 2025). Existing oTPD designs in STEM education contexts have been primarily delivered in either asynchronous or synchronous modalities. While

asynchronous environments support self-paced engagement, sustained reflection, and access to archived resources that teachers can revisit over time (Clark & Mayer, 2024; Hernandez et al., 2024; Moore et al., 2024), synchronous environments can provide collective goals, social presence, and real-time dialogue and feedback that help sustain PLCs (Clark & Mayer, 2024; Jin et al., 2024; Mulaimović et al., 2024). Designing these modalities in isolation makes it difficult for teachers to connect individual sensemaking to collective inquiry, especially under high demands and time pressure (Tuohilampi et al., 2024).

This challenge is exemplified in bioinformatics, an emerging interdisciplinary STEM field integrating biology, computational thinking, and data science that is currently underrepresented in K-12 curricula (Yoon et al., 2025). Unlike more established STEM domains such as physics or chemistry where CK and PCK bases, curricular frameworks, and instructional exemplars are well-developed, bioinformatics is rapidly evolving and lacks a standardized K-12 knowledge base. Under these conditions, teachers benefit most from opportunities to learn through both delayed and real-time collaborative inquiry with STEM professionals and peers (Chan et al., 2025; Lo et al., 2021; Rosen & Vasconcelos, 2025; Yoon et al., 2025). To better support STEM teacher learning in oTPD settings, bichronous learning, which intentionally blends asynchronous and synchronous activities to leverage their complementary strengths, has been proposed (Martin et al., 2020). While bichronous models have been explored for language learners (Al Massalmeh et al., 2025; Ho & Hsueh, 2025) and teachers (Mohammadi, 2024) and higher education settings (Martin et al., 2023), the field lacks empirically grounded frameworks for K-12 STEM teacher PD. Although a coherent learning experience depends on the intentional coordination of these modalities (Jeong et al., 2019), it remains unclear how design decisions and orchestration principles shape teacher learning journeys and sustain teacher collaboration within bichronous learning environments.

The selection of bioinformatics as the focal STEM domain in this study is grounded in a multi-year, NSF-funded research program examining how high school biology teachers integrate bioinformatics into classroom practice (Yoon et al., 2022; Yoon et al., 2025; Yoon et al., in press). Within this program, bioinformatics offers a particularly informative case for examining bichronous oTPD design because it requires teachers to simultaneously learn unfamiliar interdisciplinary content, master authentic computational tools, and translate both into classroom practice with few established curricular resources to draw on. These same conditions that make bioinformatics challenging to teach are precisely the conditions under which the coordination of asynchronous reflection and synchronous collaboration matters most. This study examines an online bichronous PD program supporting high school science teachers in developing bioinformatics expertise and implementing a STEM integrated curriculum. Analyzing teacher discourse across asynchronous and synchronous spaces, the study asks: How does a bichronous online PD model support teachers' developing bioinformatics CK and PCK through collaborating across asynchronous and synchronous modalities? The findings offer design insights for cohesive, time-efficient oTPD models that promote teacher growth and establish PLCs in interdisciplinary STEM fields.

Conceptual Frameworks

Online Teacher Professional Development for STEM Integration

While oTPD offers anytime, anywhere accessibility, its convenience is often undermined by the autonomy paradox (Stavermann, 2025). Teachers frequently struggle to self-regulate learning amidst demanding workloads, often pushing PD participation into unpaid personal time (Creagh et al., 2025; Tuohilampi et al., 2024). Without intentional design that accommodates these constraints, the deep reflection and iterative application necessary for professional growth remain elusive.

Effectiveness in oTPD depends on moving beyond static, one-size-fits-all workshops toward models that prioritize long-term, contextualized support (Bragg et al., 2021; Jin et al., 2024; Lay et al., 2020; Meyer et al., 2023). To be transformative, oTPD must foster competence and confidence in both CK and PCK (Yoon et al., 2025). In the context of bioinformatics, a field characterized by its interdisciplinary reliance on genetics, molecular biology, and computational modeling, this requirement is twofold: Bioinformatics CK refers to understanding the fundamental tools and methodologies used to process biological data through computational approaches. Bioinformatics PCK refers to the ability to translate these complex datasets into instructional strategies, such as Problem-Based Learning (PBL) centered on socioscientific issues.

Public health challenges like the relationship between asthma and air quality in urban areas are complex, controversial problems that bridge scientific concepts with ethical, social, and political considerations. Engaging students with personally relevant topics fosters scientific literacy and interdisciplinary skills through evidence-based reasoning and authentic inquiry, while also cultivating interest in STEM and demonstrating how science responds to real-world dilemmas (Yoon et al., 2022). Teaching these interdisciplinary domains requires teachers to engage as learners themselves and become active designers of inquiry-based experiences. However, many existing models fail this transition due to a lack of hands-on application and a disconnect between the theoretical STEM concepts learned and the practical realities of classroom implementation (Chan et al., 2025; Lo, 2021; Rosen & Vasconcelos, 2025; Yoon et al., 2025).

Effective STEM-focused oTPD must, therefore, transform self-regulated learning into structured opportunities for collaborative knowledge construction. High-quality models optimize teacher time by blending scaffolded lesson design with expert-led mentorship within a sustained PLC. By providing environments where teachers engage with authentic data as learners first before modifying lessons as designers, oTPD can bridge the gap between emerging scientific practices and K-12 classroom instruction (Yoon et al., 2022).

Affordances and Constraints of Existing Online Modalities

The efficacy of oTPD depends on how it leverages the distinct affordances of asynchronous and synchronous modalities while mitigating their respective constraints (Jeong et al., 2019). The two modalities offer largely complementary strengths and weaknesses. Characterized by temporal and spatial flexibility, asynchronous learning

enables the iterative, sustained reflection necessary for mastering complex STEM concepts, supports permanent repositories of recorded videos and lesson exemplars, the curation of peer-contributed resources, and allows facilitators to scaffold collaborative knowledge construction through moderated discussion forums and purposeful prompts (Clark & Mayer, 2024; Hernandez et al., 2024; Meyer et al., 2023; Moore et al., 2024). However, the absence of real-time interaction and the high demand for self-regulation can produce professional isolation, sporadic participation and fragmented learning trajectories. Synchronous learning addresses these constraints by leveraging immediacy to foster social presence and accountability (Clark & Mayer, 2024; Martin et al., 2020). Live sessions provide just-in-time expert scaffolding, modeling of instructional strategies, clarifying misconceptions as they arise, and building the professional rapport and trust necessary for sustained PLCs (Clark & Mayer, 2024; Jin et al., 2024; Mulaimović et al., 2024; Stavermann, 2025). Yet, fixed meeting times often conflict with teaching responsibilities, and the fast-paced nature of live STEM sessions can lead to virtual fatigue and cognitive overload. Because the constraints of each modality are addressed by the strengths of the other, a bichronous approach offers a more comprehensive path for effective oTPD.

Designing Bichronous Teacher PD for STEM Integration

Bichronous learning is defined by the intentional sequencing and integration of these modalities to create a balanced, cohesive online experience (Al Massalmeh et al., 2025; Ho & Hsueh, 2025; Martin et al., 2020; Martin et al., 2023; Mohammadi, 2024). Unlike fragmented models that treat the two components as parallel tracks, a bichronous approach focuses on orchestration principles, time-based decisions that ensure participants transition seamlessly between deep reflection and real-time interaction (Meyer et al., 2023).

The conceptual contribution of bichronous learning design is cross-modal coordination, a self-reinforcing loop that lies in specifying how activity in one modality feeds into and is consolidated by activity in the other (Martin et al., 2023). Three transitions characterize this coordination. In asynchronous preparation, teachers engage deeply with complex STEM content as learners and surface initial questions, tensions, and pedagogical uncertainties through reflection and forum discussions. In synchronous real-time collaboration, those surfaced uncertainties become the agenda for live sessions where facilitators and subject matter experts resolve CK and PCK related inquiries, demonstrate teaching moves, and support collective troubleshooting. In asynchronous reintegration, the insights generated in real-time return to the forum space where teachers translate them into ready-to-implement instructional plans and share peer feedback that extends the live conversation into community-owned artifacts. Synchronous sessions are meaningful only when asynchronous reflection has identified what needs to be discussed, and synchronous decisions become productive only when asynchronous reintegration converts them into refined practice.

By aligning anytime flexibility with real-time accountability, the bichronous model transforms oTPD from a series of isolated events into a sustained PLC. This intentional orchestration minimizes the autonomy paradox by providing enough structure to drive CK and PCK development while maintaining the flexibility required by

demanding instructional schedules (Jeong et al., 2019). Crucially, this model promotes interactional buildup, the continuous growth of collective knowledge across time and space (Martin et al., 2023). This synergy is essential for mastering emerging STEM domains where the knowledge base is rapidly evolving and requires constant collaboration with subject matter experts and like-minded peers.

Methods

Pedagogical and Instructional Design

This study analyzed a four-week, 60-hour PD course on bioinformatics for high school science teachers, hosted on edX Edge in July 2020. Developed through an NSF-funded project, this iteration transitioned from a 2019 in-person pilot to an online bichronous learning model. This shift aimed to provide more flexible, sustained support for teachers facing challenges in mastering bioinformatics proficiency and translating content into classroom practice (Yoon et al., 2022).

The course aimed to develop teachers' bioinformatics CK and PCK and establish a PLC that integrated data literacy, computational literacy, and mobile learning into classroom practice. To move from theoretical understanding to practical application, teachers analyzed local air quality data using digital visualization tools, investigated genetic, environmental, and sociopolitical intersections, and collaboratively designed a PBL unit aligned with their school curriculum standards and classroom contexts (Yoon et al., 2022).

The instructional design combined asynchronous modules with weekly live sessions to create a continuous learning loop. This dual-layer approach minimized barriers with context switching and preserved interactional history across modalities. The asynchronous layer used threaded forums with search functions and embedded multimedia resources such as lecture videos, infographics, articles, and teaching materials. These resources prompted teachers to initiate conversations, revisit prior contributions, and build shared resource collections. Platform notifications supported re-entry and kept distributed participation coordinated. The synchronous layer employed integrated real-time video sessions with screen sharing for collaborative problem-solving, facilitator-guided Q&A with subject-matter experts, and live chats to further discussions. Session discussions, then, re-entered the asynchronous workflow, serving as seeds for further discussions.

Participants

The participant cohort consisted of nine high school (9th-12th grade) biology and environmental science teachers from Northeastern US. Their teaching experience ranged from 2 to 14 years, with an average of 5 years. The group included five female and four male teachers. School placements included seven public, one private, and one charter. All teacher participants completed asynchronous assignments and joined weekly synchronous meetups. Detailed demographic information is provided in Table 1.

Table 1*Participating Teacher Information (N = 9)*

Teacher ID	Gender	Teaching Years	School Type
Teacher 1	Female	5 years	Private High School
Teacher 2	Female	2 years	Charter High School
Teacher 3	Female	10 years	Public High School
Teacher 4	Female	2 years	Public High School
Teacher 5	Female	4 years	Public High School
Teacher 6	Male	6 years	Public High School
Teacher 7	Male	2 years	Public High School
Teacher 8	Male	2 years	Public High School
Teacher 9	Male	14 years	Public High School

The research team purposefully recruited a small, highly motivated cohort distinguished by strong interest and capability in navigating and integrating interdisciplinary STEM content which aligns with recommendations for early-stage exploratory design work (IES & NSF, 2013). The focus was on deep, qualitative insights rather than broad generalizability. Inclusion criteria required that eligible participants were required to be current high school biology or environmental science teachers with an interest in bioinformatics and a commitment to implementing a PBL unit in their classrooms during the following academic year. Candidates first submitted a formal application with their teaching background. This was followed by interviews with the research team to assess their readiness for the intensive PD program.

To support these participants within the bichronous learning environment, the research team established a PLC with multiple stakeholders involved. The nine primary teacher participants collaborated with the research team who acted as moderators for asynchronous discussion forums and facilitators for live synchronous sessions; subject matter experts who provided theoretical and technical guidance on bioinformatics content and the use of mobile air quality sensors; and two teacher facilitators from the previous cohort, both of whom had been nominated by the director of science in the school district for their teaching expertise. They served as peer mentors to bridge the gap between theory and classroom reality.

Data Sources

The study used two primary data sources to capture the dynamic interactions within the bichronous PLC. Data sources were divided into asynchronous forum contributions and synchronous session recordings.

Asynchronous Discussion Forum Data

The data source for examining asynchronous teacher engagement consisted of 52 discussion forum prompts across eight modules. These prompts yielded a total of 1,363 participant responses, categorized as top-level posts, second-level comments, and third-level replies. Each module contained approximately six prompts, ranging from five to

eight. The prompts were designed to fulfill two pedagogical functions: content reflection and implementation. These prompts aimed to foster teacher collaboration in building CK and PCK. Detailed discussion forum prompts information is provided in Table 2.

Table 2

Asynchronous Discussion Forum Prompts Information (N = 52)

Prompt Type	Total Number	Focus	Example
Content Reflection	19	Focused on CK building	Post at least one general and one specific example of exposure that a high school student may encounter in daily life. Describe the potential long-term and short-term health outcomes for an individual, then respond to your peers' connections.
Implementation	33	Focused on PCK building	What new ideas or challenges do you consider when integrating the exposome concept into your existing air pollution lessons? Identify two outside sources you could use and respond to peers' posts.

Synchronous Session Data

To capture real-time collaboration, the research team analyzed five synchronous session video recordings including one orientation, three weekly morning meetings, and the final meetup. The synchronous sessions ranged from 28 to 50 minutes in length, totaling 205 minutes, and included content discussions, announcements, check-ins, Q&A, and feedback. Detailed session information is provided in Table 3.

Table 3

Synchronous Session Information

Session	Session Type	Duration	Key Activities	Participants
1	Orientation	32 min	Norm setting, platform walkthrough	Teachers, research team, teacher facilitators
2	Weekly check-in	50 min	Content Q&A, Facilitator-led reflection and discussion	Teachers, research team, teacher facilitators, subject matter experts
3	Weekly check-in	47 min		
4	Weekly check-in	48 min		
5	Final Meetup	28 min	Program wrap-up and feedback	Teachers, research team, teacher facilitators, subject matter experts
Total		205 min		

The sessions were conducted and recorded via a video conferencing platform. For analysis, initial transcripts were generated using Otter.AI. To ensure accuracy, the first author with two graduate students manually reviewed and cleaned each transcript by cross-referencing the video.

Data Analysis

The study conducted a hybrid deductive-inductive thematic analysis following the six-stage of data coding established by Fereday and Muir-Cochrane (2006). This approach integrated data-driven codes emerging from the unique bichronous environment with theory-driven ones from high quality teacher PD principles (Darling-Hammond et al., 2017).

Developing and Validating the Code Manual

The first author developed two parallel code manuals for asynchronous and synchronous modalities. Each code was defined with a clear label, a definition, a description of indicators to recognize the theme, and examples. Detailed code manual information is provided in Tables 4 and 5. Codebook development and validation proceeded over a full academic semester through an iterative, multi-step process designed to establish both internal coherence and inter-coder agreement.

In the first step, the first author drafted an initial coding scheme grounded in the high-quality teacher PD principles articulated by Darling-Hammond et al. (2017) and the bichronous learning literature (Martin et al., 2020; Martin et al., 2023). This preliminary scheme was refined across multiple weeks of iterative application with two trained graduate students, who independently coded successive samples of asynchronous forum posts and synchronous session transcripts. After each round, the team convened to reconcile coding disagreements, clarify category boundaries, and revise definitions and indicators. For the asynchronous manual, an overlap was identified between Archives of Activities and Instructional Artifacts and Sharing of Instructional Supports. The former was narrowed to tangible digital artifacts such as hyperlinks to external sources and teacher-created documents while the latter was redefined around teachers' shared pedagogical moves, instructional strategies, and classroom practices. For the synchronous manual, a parallel distinction was drawn between Professional Collaboration and Community Building and Increased Engagement through Social Interactions. The former was revised to prioritize peer-to-peer interactions including collective reflection and the sharing of classroom experiences while the latter was refined to focus exclusively on facilitator-led strategies intended to sustain participant motivation and social cohesion.

In the second step, the codebook underwent expert validation with the second and third authors, who had collected the original data in a prior phase of the research program and were familiar with the corpus. Validation proceeded through a series of structured meetings in which the first author shared illustrative excerpts paired with proposed code assignments and supporting rationale across each category. The second and third authors reviewed these examples against the codebook definitions and indicators, raised boundary cases, and contributed alternative interpretations. Definitions were revised iteratively until all three authors reached consensus on the scope and indicators of each category.

In the final validation step, the second author was provided with the refined codebook and a sample of previously uncoded asynchronous and synchronous excerpts. Working independently, the second author classified each excerpt

by modality and applied the relevant codes without access to the first author's prior assignments. Given the extended iteration in the earlier steps, no discrepancies emerged between the first and second authors' independent coding of the validation sample. The full corpus was then coded using this validated codebook with analytic memos and weekly review meetings continuing to support consistent application throughout full-scale analysis.

Table 4
Asynchronous Learning Code Manual

Category	Description	Example
Reflection	<p>Instances where participants engage in reflective thinking related to their CK and PCK. This includes expressing insights, evaluating teaching practices, and drawing connections between course content and their own classroom contexts. As defined by Darling-Hammond (2017), this involves “Describing the elements of the activity that extended their learning and considering implications and adaptations of the pedagogy for their classrooms.” Reflective responses may articulate tensions, goals, or aspirations for improving instruction, often grounded in specific teaching experiences or instructional decisions.</p>	<p>“Both real world and teamwork aspects will lead students to learn these skills and develop them further for the rest of their lives. [City] does have a high pollution and asthma rates as there are many chemical companies and manufactures right there close to neighborhoods making this an authentic problem for students to investigate and help find solutions. Also, by working together in teams they can use their collective knowledge/ways of thinking which is always much richer in scope and depth which leads to connections between people, and also how they have these problems/issues and are working together to find/develop real solutions.” The teacher participant reflects on both the content relevance (e.g. authentic, place-based learning around asthma and pollution) and the pedagogical strategy (e.g. teamwork, collective knowledge-building). This reflection illustrates how pedagogical design and local context inform each other.</p>
Archives of Activities and Instructional Artifacts	<p>Instances where the learning space functions as a shared digital repository for participants to store, revisit, and reuse instructional materials and interactions. This includes discussion forum responses, multimedia resources, hyperlinks, lesson plans, data sets, and documents shared by teachers. Such archives support what Darling-Hammond et al. (2017) describe as sustained engagement with high-quality curricular resources and opportunities to examine and reflect on practice over time.</p>	<p>“[US black and Hispanic minorities bear disproportionate burden from air pollution][1] [1]: https://www.sciencedaily.com/releases/2019/03/190311152735.html. Here would also be an opportunity to talk about the burden of disease maps and information on a global scale.[Burden of Disease][2]: https://ourworldindata.org/burden-of-disease/ The teacher participant contributes two external resources that link air pollution and public health outcomes to broader societal patterns. By embedding hyperlinks and suggesting potential use for them in instruction, the teacher is curating digital resources that others can revisit and build on.</p>

Sharing of Instructional Supports	<p>Instances where participants contribute to the PLC by sharing their “I think Asthma is a serious issue everywhere- some places have very high occurrences. I believe this because there are national daily forecasts for air quality in every city daily and the EPA monitors this as well.</p> <p>To introduce this topic I could have students read [US black and Hispanic minorities bear disproportionate burden from air pollution][1] . I would have to remind students of expected behaviors and appropriate language during open (semi- controlled) discussions so we look at the facts and why this is because this is a hot topic. Here would also be an opportunity to talk about the burden of disease maps and information on a global scale.[Burden of Disease][2]</p> <p>At some point I would add in both D's simulation video and S's [City] statics- thanks for the info.</p> <p>The teacher participant shares a detailed instructional approach to introducing a socio-scientific issue with national data, discussion norms, global comparisons, and peer-contributed resources. It demonstrates how teachers collaboratively shape pedagogy in context.</p> <p>“Hey D, QTEL, I never heard of it. I'm going to have to look into it. Anyway, to help students learn vocabulary and the content better is worthwhile. Have you been able to implement QTEL before we left school? Were the students responsive to it? I'm interested to know how the concept translated in [City] high schools.”</p> <p>The facilitator models curiosity and pedagogical inquiry by posing reflective questions about the use of QTEL. They share their own perspective and invite further conversation around implementation and student responsiveness.</p>
Access to Facilitation	<p>Instances where participants interact with or benefit from structured support provided by facilitators, the research team, or embedded program features (e.g. Q&A forums, moderated discussion prompts, feedback, capstone guidance). Facilitation involves monitoring, prompting, and sustaining engagement, often through clarifying content offering targeted feedback, or guiding peer interaction. According to Darling-Hammond et al. (2017), facilitation is essential to “supporting group discussion and collaborative analysis of [participant] work.” This category captures moments where facilitator presence shapes the direction, depth, or coherence of professional learning.</p>

Peer Support	<p>Instances where teacher participants provide acknowledgement, encouragement, agreement, appreciation or express uncertainty, concern, or vulnerability in response to their peers. These teacher-to-teacher interactions foster a supportive PLC by validating experiences, normalizing challenges, and reinforcing a sense of shared purpose. While they may not directly advance instructional content, they contribute to the social-emotional foundation of teacher learning. Darling-Hammond et al. (2017) describe these as “opportunities to share both positive and constructive reactions to authentic instances of teacher practice,” which are essential for building trust and psychological safety in collaborative settings.</p>	<p>“Thanks for sharing the response! I would have no idea how to help someone with asthma if they were having an attack, and like I mentioned in an earlier post I have many students with asthma so this is very informative... With the uncertainty of what the school year will look like I am nervous that completing a PBL unit completely online may bring challenges and hardships for both me and my students that may be unforeseen currently. That being said, I am excited to have my students look at a problem that is so relevant to their city, and potentially have them get involved in finding a solution.”</p> <p>The teacher expresses gratitude by validating the usefulness of a peer’s post while expressing their own instructional need. They also express vulnerability and hope by acknowledging concerns about virtual implementation while affirming the relevance of the PBL unit. It demonstrates how peer support creates space for teachers to feel seen, supported, and connected.</p>
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Table 5*Synchronous Learning Code Manual*

Category	Description	Example
Real-Time Collective Problem Solving	Instances where participants engage in immediate, practical collaboration to identify issues, solve logistical problems, and adjust instructional practices based on shared experiences and peer input in real-time. This includes collaborative discussions addressing specific technological, instructional, or logistical challenges; group troubleshooting and brainstorming solutions for classroom implementation; facilitator scaffolding grounded in direct classroom experiences. This category reflects Darling-Hammond et al. (2017)'s three design elements: collaboration through joint lesson planning and cooperative problem-solving activities; active learning as teachers actively design and refine instructional strategies in real time; and content focus with discussions anchored in subject-specific instructional strategies and curriculum integration.	“A question on distribution of the cell phones and the sensors: If we go virtual, how will we even get the technology to [students]?” The logistical constraints of remote learning prompted teachers to explore creative and practical solutions for engaging students with the air quality sensors. It transforms an individual concern into a site of shared problem-solving across the cohort.
Immediate Feedback and Expert Access	Instances where facilitators and subject matter experts provide real-time, targeted feedback, practical guidance, and explicit demonstrations that enable immediate clarification, deeper understanding, and adaptive instructional practices. This includes immediate responses to participant questions and misconceptions, explicit modeling of pedagogical strategies, direct address of technological and logistical issues, and real-time demonstrations of instructional strategies and tools such as digital platforms, data analysis workflows. This category reflects Darling-Hammond et al. (2017)'s three design elements: coaching and expert support through tailored guidance provided by facilitators; feedback and reflection as immediate, formative feedback is provided in response to teacher questions and uncertainties; and use of models and modeling with facilitators demonstrating instructional best practices and technological use.	The facilitator offered an in-depth walkthrough including its practical classroom applications, explaining, “So for students [without much coding experience], we could have a place where they can just go and learn things on their own or explore beyond what’s in the classroom. That was the goal of this exploratory data analysis.” The walkthrough during the synchronous meetup goes beyond the basic instructions provided on the MOOC platform by connecting the website’s features to real-world classroom applications. It illustrates how synchronous expert access translates technological resources into pedagogically meaningful tools.

Professional Collaboration and Community-Building	<p>Instances where structured or spontaneous interactions build professional networks, foster ongoing collaborative relationships, and support peer-to-peer professional growth and resource sharing. This includes explicit encouragement of peer-to-peer interactions and resource sharing, structured support for forming teacher partnerships or affinity groups, and facilitator-prompted collective reflection on classroom experiences. This category reflects Darling-Hammond et al. (2017)'s three design elements: collaboration through intentional design supporting community-oriented professional dialogue; sustained duration as ongoing interactions across sessions build deeper professional relationships; and feedback and reflection with peer-to-peer feedback and collaborative reflection on instructional practices and experiences forming the substance of those interactions.</p>	<p>One teacher reacted, "The exposure was something I'd never heard of either... I really appreciate learning all these new environmental science concepts, which I'd like to tie more into biology classes." Another teacher added, "[My students] are really excited to learn it."</p> <p>The program provides a space for shared experiences and mutual support. The teachers' willingness to share their learning experiences and their enthusiasm for applying new concepts to their classrooms reflect a collaborative and supportive atmosphere. It demonstrates how synchronous interaction creates space for shared professional identity formation alongside content engagement.</p>
Increased Engagement through Social Interactions	<p>Instances where interactive and social strategies sustain participant involvement, active contribution, motivation, and accountability throughout sessions. This includes regular structured check-ins and open-ended questions promoting active participation, informal facilitator strategies that enhance a socially engaging atmosphere such as humor and informal dialogue, and consistent facilitator responsiveness that models active participation.</p>	<p>During the last synchronous meetup, a facilitator informed the participants, "We have some pre-scheduled Saturday meetups to give you extra support or share updated information. These meetings are for Cohort One teachers to ask questions or share exemplars."</p> <p>The facilitator's framing extended the PD program into an ongoing, voluntary structure. It encourages participants to remain actively involved in the professional learning community and maintain their connections with peers and facilitators while continuing to refine their practices.</p>

Thematic Synthesis and Modeling

The thematic analysis proceeded from identifying initial themes to identifying cross-modal patterns. Asynchronous forum responses were organized by module and categorized the discussion forum into either content reflection or implementation. Synchronous sessions were transcribed with a comprehensive overview for each session. The transcripts included a summary of the session's primary objectives, a list of action items discussed, and a chronological outline of the main discussion topics.

While the formal coding process was guided by the codebooks, the research team also employed inductive coding to capture novel pedagogical or interactional practices not present in the initial manuals. For asynchronous data, the research team observed teacher interactions that were non-content related but essential for validating experiences and building rapport. The code Peer Support was added to the manual to capture this social-emotional foundation of the PLC. For synchronous data, initial codes for collaboration were refined after observing instances of specific technical troubleshooting and logistical adjustments during live sessions. This led to the creation of the data-driven code Real-Time Collective Problem Solving. The team kept analytic memos to document coding decisions, boundary cases, and cross-references between modalities. Weekly review meetings were held to reconcile disagreements, refine definitions, and stabilize category use.

To identify underlying relationships, the research team clustered codes based on their complementarity and temporal sequencing. The research team examined how specific codes in one modality facilitated or resolved issues in the other. For instance, the team traced how asynchronous Reflection codes often preceded and informed synchronous Immediate Feedback and Expert Access codes. Through iterative memo writing and research team discussions, these patterns were synthesized into an explanatory model of the bichronous learning ecology. The two interlocking pathways constituted the bichronous PD model. The Flexibility Pathway captured how temporal flexibility allowed teachers to process complex concepts and co-construct bioinformatics CK and PCK at their own pace. The Immediacy Pathway captured how live sessions provided necessary just-in-time expert support and opportunities for collaborative decision-making. These pathways formed a self-reinforcing iterative sequence that sustained the virtual PLC.

Results

The findings are organized into three analytically sequential phases that trace how teachers' learning moved across modalities within the bichronous design. Phase 1: Asynchronous Foundation Building captures how the Flexibility Pathway enabled self-paced content engagement and collaborative knowledge construction. Phase 2: Synchronous Synthesis captures how the Immediacy Pathway provided real-time expert scaffolding and collective problem-solving. Phase 3: The Bichronous Iterative Loop demonstrates how these pathways formed a self-reinforcing cycle, with insights generated in one modality shaping participation in the other. These phases reveal how the bichronous model supported the co-development of bioinformatics CK and PCK within a sustained professional learning community.

Phase 1: Asynchronous Foundation Building

The asynchronous forums served as the primary site for developing bioinformatics CK and PCK through three escalating processes: teachers first engaged in situated reflection on content, then deepened their engagement through peer support, and ultimately preserved their collective work as archived resources for future classroom use. Across 52 discussion prompts, teachers generated 413 discussion threads (averaging 8 per prompt), with 250 threads (61%) containing more than three levels of replies indicating sustained collaborative dialogue rather than isolated responses.

Temporal Flexibility Scaffolded Collaborative CK and PCK Building

The temporal flexibility of asynchronous forums enabled a three-tiered reflective process through which individual content engagement escalated into collaborative CK and PCK construction. This progression was visible in the hierarchy of replies across discussion threads. Top-level posts functioned as initial content reflection, with teachers connecting course concepts to their classroom contexts. For example, in the discussion prompt Day to Day Exposures (3.3.1), teachers were asked to connect the concept of the exposome to high schoolers' daily lives. One teacher, Teacher 7, initiated a thread by connecting the prompt to socioeconomic factors and specific risk behaviors prevalent in their school:

Teacher 7 (Level 1 Post): Focusing on differential household incomes ... if a family is struggling financially they may not go to the doctor when they feel sick ... So now an infection becomes worse ... It is no surprise, but many students are addicted or heavy users of E-cigarettes and vaping ... even more so than traditional cigarettes.

Teacher 7 is situating the bioinformatics content (i.e., exposures) within the socio-economic reality of their students including healthcare access and vaping addiction.

Second-level comments transformed these reflections into shared professional knowledge through contextual validation. Peers did not simply acknowledge the post; they expanded its scope by adding their own instructional contexts. In response to Teacher 7, peer Teacher 2 connected the topic to a specific pedagogical tool, commenting, "E-cigarettes and vaping is a great specific exposure to point out. We watch CNN 10 in the morning, and the reports about the dangers of smoking e-cigs and vaping definitely caught their attention," while peer Teacher 5 reinforced the situated nature of the reflection by referencing their Title 1 school context and posing a critical question about corporate ownership of vaping companies, saying "Lots of great points here, my school is a title 1 - so most struggle financially. Families' ability to have healthcare does concern me. I wonder who owns these companies?" Teacher 2 and Teacher 5 expanded the scope of reflection from health outcomes to instructional strategies and systemic inequity. These responses shift the tone from individual reflection to community validation.

Third-level replies then deepened the inquiry toward co-constructed CK and PCK. The third level of interaction often signaled a shift toward deeper inquiry or the integration of subject matter expertise. In this thread, the discussion evolved from identifying the problem to analyzing the corporate ethics behind it, a complex nature of science discussion triggered by Teacher 5's question in Level 2.

Teacher 7 (Level 3 Reply): One of the funniest moments this past year was talking about ethical studies and when students found out JUUL was owned in majority by Marlboro the cigarette company it had this profound effect on the discussion then when we said the companies 'own studies' showed no bad effects of vaping.

Then, Teacher 3 replied, "Vaping is the new thing with cigarette companies ... The worst part is that they are targeted to the vulnerable teen market so they can get hooked for the rest of their lives." Simultaneously, the subject matter expert utilized this depth to validate the scientific relevance of the teachers' knowledge, replying, "Agreed, vaping is certainly a timely and relatable specific exposure that can be focused on. Potentially it's an opportunity to think about the long term negative health consequences ... " Through this leveled structure, teachers moved from identifying a biological concept to critiquing the systemic forces affecting their students, to co-constructing a richer, more contextualized understanding that integrated both CK (i.e., environmental exposures and health outcomes) and PCK (i.e., how to make these concepts resonant for students).

Peer Support Transformed Individual Insights into Shared Instructional Resources

Building on situated reflection, peer support served as the mechanism that transformed individual insights into shared community resources. This was most visible in the Teaching Air Pollution thread (3.3.3), which contained all nine participants across 11 responses. Teacher 3 described a specific, low-cost activity of creating "homemade indoor particulate air pollution collectors" using index cards and packing tape. While valuable, as a standalone post, it remained an isolated anecdote. However, the second and third-level responses transformed it into a collectively refined PCK resource. For instance, Teacher 7 combined validation with a specific request for materials and a connection to data analysis standards:

Teacher 7 (Level 2 Comment): Teacher 3, this is such a great activity! Would you be interested in sharing your instructions/templates you have on this? Especially for schools that don't necessarily have the funding for a lot of materials ... maybe even extrapolation concepts could be introduced.

Then, Teacher 5 identified their aging building as a data collection site. Teacher 4 suggested relocating the lesson from Environmental Science to a Biology unit on the Scientific Method, broadening its applicability. Critically, the original poster remained engaged: when Teacher 8 proposed having students write placement proposals, Teacher 3 immediately integrated the feedback, replying "Teacher 8, I love the idea of having them write a proposal for the placement. This really forces the students to think about air circulation." This pattern of validation followed by expansion followed by integration illustrates how peer support provided the psychological safety and collective interest necessary to turn one teacher's PCK into a community-owned instructional asset. The asynchronous format

gave teachers the time to craft thoughtful adaptations rather than responding extemporaneously, a condition that created productive material for later synchronous discussions.

Discussion Forums Functioned as a Living Resource Archive

The culmination of situated reflection and peer support was a dynamic digital repository that preserved both content resources and the pedagogical reasoning for their use. In the *Resources for Introducing Asthma* thread (2.2.2), Teacher 7 archived a local news article embedding it as a hyperlink that peers could revisit, “... I found reports that [City] is the 3rd most challenging place in the U.S. to live in ... In fact, this article [URL] from 2019 says 1 in 4 kids in [City] are diagnosed with asthma.” Teacher 4 immediately recognized it by responding, “Thanks for providing a great hook for introducing asthma as an SSI.”

In a parallel thread, Teacher 9 contributed a CDC data resource connecting asthma to cellular respiration by posting, “One resource that has a lot of data and other solid info is: [URL]. The data includes state numbers of those with reported asthma vs. the whole state population.” It prompted Teacher 7 to layer a more technical NIH research article while simultaneously suggesting scaffolding strategies for high school students, commenting, “This article may be a bit complex for high school students, but you could show them the data and graphs ... [URL].” These exchanges illustrate the dual function of resource archiving: it preserved both the CK content and the PCK strategy. The forum thus served as a living curricular library that remained accessible beyond the initial discussion and that later synchronous sessions could draw upon when addressing implementation challenges.

Phase 2: Synchronous Synthesis

While asynchronous forums established the reflective and archival foundations, the synchronous sessions provided the immediacy necessary for expert scaffolding, collective problem-solving, and community-building. Importantly, these sessions did not operate independently from the asynchronous work; facilitators routinely drew on specific forum threads to structure live discussions, ensuring continuity between modalities.

Real-Time Expert Scaffolding Bridged CK-to-PCK Translation Gaps

Facilitators used synchronous sessions to address misconceptions and pedagogical uncertainties that had surfaced in asynchronous forums, providing real-time scaffolding that the asynchronous modality could not deliver. The most prominent example involved PBL implementation. In the asynchronous forum thread 2.3.1, Teacher 6 had expressed skepticism that PBL was unsuitable for students lacking foundational skills. Rather than letting this deficit-model framing persist, the facilitator explicitly anchored the next synchronous session in Teacher 6's post:

I wanted to talk about a post that Teacher 6 made ... I appreciated your concern about what happens when you have a population of students who do not have that self-organized skill set ... [But] PBL is not an anything goes pedagogy. It is highly scaffolded ... You are scaffolding the groups, the questions ... what is different is that you're embedding this in a problem that they have a choice in solving.

This intervention validated the teacher's concern while immediately reframing PBL from an unstructured risk to a highly scaffolded instructional design, directly addressing a CK-to-PCK translation gap.

The facilitator then elevated the discussion by outlining the cognitive science behind PBL, using hand gestures to map relationships between working memory and long-term memory, explaining why the program selected asthma as an anchor:

If you can retrieve what has been stored in your long term memory, into your working memory, there is a negotiation that happens a lot faster ... With problem based learning, the idea is that you're creating a cognitive scaffold ... through which new information can now continue to be added.

Structurally, the facilitator acted as an orchestrator of expertise. After establishing this theoretical framework, the facilitator strategically ceded space to teacher facilitators, who provided practical evidence from their classrooms. This layered approach of subject matter experts providing the theoretical rationale and teacher facilitators providing the practical demonstration ensured that participants received cohesive, evidence-backed PCK for implementation.

Collective Problem Solving Enabled Rapid Prototyping

While expert scaffolding operated within a facilitator-led hierarchy, collective problem-solving captured moments where that hierarchy flattened and participants collaboratively addressed logistical and technological challenges. This dynamic was most evident following the completion of Modules 5 and 6, which introduced mobile learning using air quality sensors. The central challenge was reconciling the curriculum's requirement for physical data collection with the possibility of fully virtual instruction due to COVID-19.

When the facilitator suggested providing pre-collected datasets as a compromise, explicitly noting this would reduce engagement because it would not be the students' own data, teacher participants rejected the compromise and rapidly prototyped alternatives:

Facilitator: How would we do the mobile learning part? Is this the toughest one to implement? ... giving them pre-collected data, and using that would probably be the best way?

Teacher 7: But I was thinking, take mobile learning to like, the next step was students being very social... My mindset was going with having students give me a list of places they would like to collect data. And then I would like to live stream, going there and collecting the data. And then that way, there's some like collection that they get to be kind of involved with... So still getting some collection that they chose where to be and where they would like to collect data from?

Facilitator: Oh, I love that. That's a great idea!

Teacher 5: Yeah, I think that's great, too. During COVID, I dropped stuff off [at] the kids houses... Actually, it was their prizes, food and whatnot... But anyway, why can we just drop it off at selected ones, and then pick it up and take it to another student? I mean, I'd rather them be involved or try to

see things, get the app on their phone, drop off a sensor? I mean, why don't we take it to the next level?

Teacher Facilitator: If we can, I think it really depends on whether we're in a lockdown or not.

Because if we're just virtual, but the current rules are in place, I think the kids might be able to pick up and use the sensors on their own... But I don't know if that could all change from week to week.

Teacher 7 proposed livestreaming data collection from locations students selected, preserving student agency within safety constraints. Teacher 5 escalated further, drawing on personal experience of delivering materials to students' homes during lockdown to advocate for physically distributing sensors. The teacher facilitator then grounded these ideas in policy realities, distinguishing between virtual instruction and full lockdown scenarios. Through this exchange, the group transformed a potential curricular loss into a set of adaptable strategies including livestreaming, rotation, or drop-offs calibrated to varying restriction levels. The synchronous format enabled the rapid iteration and building upon each other's ideas that asynchronous forums could not replicate, while the solutions generated here would re-enter the asynchronous workflow as seeds for individualized implementation planning.

Synchronous Interaction Built Social Connections for Sustained Participation

The synchronous sessions also functioned as the primary site for community-building that mitigated the professional isolation inherent in asynchronous learning. Sessions began with unstructured small talk: Teacher 3 sharing their vacation cabin via webcam prompted genuine exchanges about geography and work-life balance, stating, "One of the best things about working from home is that you can work from any home. I'm on vacation at our family cabin." This prompted a genuine exchange about geography ("Is that in Pennsylvania?"), signaling that the bichronous space accommodated personal schedules. Moreover, these diverse location contexts offered more opportunities to learn about the participants' non-professional lives.

Mid-way through the PD, the facilitator explicitly repositioned participants as design collaborators, inviting them to critique and improve the PD itself:

We are working with you then this other half, which is as just as a design collaborator ... we're now moving after you do this into design collaborator mode. And that means that we'll have other meetings where you're going to talk about, well, here's what the data said ... and then you could say, well, you know, we just really had problems with this part of the PD.

This move fostered ownership and mutual respect essential for sustained community engagement. The sessions concluded with plans for monthly Saturday meetups the following school year, with the facilitator articulating a vision that the PLC would evolve into a self-sustaining network extending beyond the project. These social investments, made possible by the immediacy of synchronous interaction, provided the relational infrastructure that sustained asynchronous participation between sessions.

Phase 3: The Bichronous Iterative Loop

The bichronous design's most distinctive contribution was the iterative loop through which insights generated in one modality were transported, refined, and validated in the other. Topics that emerged tentatively in asynchronous forums were clarified through synchronous expert scaffolding, then returned to asynchronous spaces as more confident, detailed implementation plans. This cycle is best illustrated through Teacher 7's learning trajectory and corroborated by cross-modal referencing patterns across the cohort.

In Week 2, during an early asynchronous discussion on PBL, Teacher 7 used the asynchronous forum to articulate a deep pedagogical tension: while intellectually understanding PBL's benefits, they struggled to shift from being a "provider of information" to a "facilitator of learning.":

I found myself this year much more in the role of 'provider of information', rather than just a tutor ...
I'd like to introduce PBL ... but the largest challenge for me and others is making the transition from knowledge provider to tutor and facilitator of learning.

This honest self-assessment, enabled by the forum's lack of time pressure, surfaced a CK-to-PCK translation gap that required targeted intervention.

In Week 3, Teacher 7 brought this concern to the synchronous meetup, asking whether PBL could coexist with existing inquiry-based methods. The facilitator responded with the cognitive science explanation described in Section 4.2.1, reframing PBL as a sophisticated scaffold rather than an abandonment of structure:

With PBL, ... you're creating a cognitive scaffold ... new information can now continue to be added ... If you're able to anchor it in some contexts, that is familiar to [your students] every time ... It supports the learning part better.

This synchronous intervention provided the theoretical anchoring Teacher 7 needed.

The third step was synchronous refinement and planning on Week 4. Equipped with this new understanding, Teacher 7 returned to the asynchronous forums to construct a highly detailed implementation plan. The tentative "provider of information" was replaced by a confident designer who integrated external resources, data ethics, and specific assessment strategies, posting, "In order to ensure students are developing an understanding of bioinformatics ... I would make sure to include constant check-ins ... I'd try to always include bioinformatic questions of themes during each lesson's warm up."

Teacher 7 constructed a detailed implementation plan incorporating constant check-ins, bioinformatics-themed warm-ups, specific trait-inventory and activities for data science practice, posting, "I use [An Inventory of My Traits] as a jumping off to discussing traits... This activity has a lot of background information present, but also allows for some data science and visualizing data practice." Regarding the practical challenges of data collection, Teacher 7 developed a concrete student accountability protocol,

posting, “The second challenge I ... KNOW will occur, is students forgetting to document their data points... For this I believe having one student be the 'checker' and I will create a step-by-step checklist that they must check after each step ... ”

By the capstone assignment, Teacher 7 presented two fully developed deployment options: an ideal sequence launching the PBL unit in March/April to coincide with genetics and use early months to build foundational skills and assess COVID feasibility, and a contingency plan introducing PBL earlier if needed. The community validated Teacher 7's preferred timeline. Peer Teacher 2 responded enthusiastically that they were "really considering stealing your idea," and the facilitator linked it to their own physics teaching experience.

Another clear marker of the bichronous ecology was when teachers explicitly referenced ideas formed in synchronous meetups and then refined them in asynchronous planning discourse. In discussion on Mobile Learning Activity Reflection (6.4.5), Teacher 6, who had been skeptical of PBL in early asynchronous posts, later explicitly referenced a synchronous session as the turning point. After describing increased optimism, Teacher 6 grounded their implementation timeline in a specific synchronous discussion, deciding to delay PBL until spring to allow time for prerequisite skills development:

The biggest challenge I foresee with my students will be access to the skills needed to complete the PBL ... In our discussion on [Synchronous Session #4], we talked about when to implement this specific PBL. I will most likely begin this PBL in the Spring. That will give me time to practice document-based questions and other PBL skills.

This decision, articulated in the asynchronous forum, was then collectively validated by peers who echoed and extended the rationale, naming concrete scaffolds, warning against premature launch, and adding motivational reasoning. The teacher facilitator reinforced the emerging consensus by offering implementation support. Through these layered responses, the asynchronous forum transformed a live feasibility conversation into a durable, community-owned instructional plan.

These patterns confirm that the bichronous design functioned as a complete learning cycle: individual uncertainty was surfaced through asynchronous reflection (Flexibility Pathway), resolved through synchronous expert support and collective negotiation (Immediacy Pathway), and then consolidated through asynchronous community validation.

Discussions and Conclusion

This study examined how a bichronous online PD model supports teachers' developing bioinformatics CK and PCK through collaboration across asynchronous and synchronous modalities. The central finding is that the program's impact did not derive from either modality alone, but from the intentional sequencing between them. This shifts the key design consideration in oTPD from modality selection to modality orchestration: how thread structures support

co-construction, how facilitators use forum data to shape live agendas, how practitioner-expert layering bridges theory and enactment, and how deliberate return paths convert synchronous insights into asynchronous refinement.

Bichronous Coordination as the Mechanism for Developing CK and PCK

Existing scholarship on bichronous learning has primarily theorized the combination of asynchronous (Clark & Mayer, 2024; Hernandez et al., 2024; Meyer et al., 2023) and synchronous modalities (Clark & Mayer, 2024; Mulaimović et al., 2024; Stavermann, 2025) as a way to leverage their complementary affordances (Martin et al., 2020; Martin et al., 2023), and empirical studies in higher education and language learning contexts have documented that bichronous designs can improve engagement and learner satisfaction (Al Massalmeh et al., 2025; Ho & Hsueh, 2025; Mohammadi, 2024). What has remained underspecified is how collaborative teacher learning occurs across modalities, particularly in K-12 STEM teacher PD contexts where empirically grounded frameworks are scarce. This study extends this body of work by suggesting that the most productive learning can occur in the transitions between them, through specific coordination mechanisms that connect participation across temporal modes. The findings reframe bichronous learning from a balanced blend of two modalities to the orchestration of cross-modal handoffs as the primary site of teacher learning.

In this study, the asynchronous forums functioned as a cumulative space for contextualizing bioinformatics CK and building transferable PCK repertoires echoing prior findings on online PD repositories (Clark & Mayer, 2024; Hernandez et al., 2024; Moore et al., 2024). The tiered reply structure revealed a consistent progression from individual content reflection to collective pedagogical reasoning, with peer support operating as a catalyst for pedagogical adaptation rather than mere encouragement. This finding extends work on online PLCs (Hernandez et al., 2024) in two ways. First, while prior studies have documented that peer interaction supports teacher learning in online settings, this study identifies psychological safety built through peer validation as a precondition for the more demanding work of co-constructing PCK. Second, while existing work on digital PD archives has emphasized resource preservation, this study extends the idea by demonstrating that the forums produced a community-authored archive that preserved resources alongside instructional annotations, not merely what to teach, but how and why a resource is pedagogically valuable. This dual layer of preserved knowledge, content paired with pedagogical reasoning, represents a critical mechanism for teacher learning in interdisciplinary contexts where standardized curricular materials do not yet exist (Yoon et al., 2022).

However, the asynchronous phase also generated uncertainties and misconceptions that required immediate, targeted resolution (Martin et al., 2023). Rather than operating as predetermined content delivery, the synchronous sessions addressed this constraint through responsive orchestration: facilitators treated asynchronous discourse as diagnostic data, designing live sessions around authentic points of confusion. This finding contributes to the bichronous learning literature where synchronous components can be described in terms of their complementarity with asynchronous activity. The layered scaffolding structure, subject matter experts providing theoretical rationale while teacher facilitators translated it into classroom-level practice, also extends Lo's (2021) design principles for STEM

teacher PD by specifying a division of expertise effective for developing CK and PCK. Synchronous sessions simultaneously built the social infrastructure of the PLC through informal exchanges and explicit repositioning of teachers as design collaborators, creating the relational conditions necessary for sustained asynchronous participation between sessions (Jeong et al., 2019; Martin et al., 2023).

This iterative loop, asynchronous reflection surfacing uncertainties, synchronous sessions resolving them, and teachers returning to forums to consolidate refined plans, constituted the program's primary learning mechanism. Individual trajectories demonstrated a transformation in professional stance, from apprehensive content learner to confident instructional designer, enabled specifically by cross-modal coordination rather than by the accumulation of experiences within a single modality. Research on oTPD has emphasized the importance of sustained collaboration and shared inquiry (Hernandez et al., 2024; Jin et al., 2024) while research on bichronous design has emphasized the structural integration of modalities (Martin et al., 2020; Martin et al., 2023). The present study integrates these strands by demonstrating that sustained PLC engagement is produced by cross-modal coordination. The data identified four coordination mechanisms driving this transformation: (1) threaded reply structures that supported escalating co-construction of CK and PCK; (2) facilitator use of forum threads as diagnostic input for synchronous agendas; (3) practitioner-expert layered scaffolding that bridged theoretical principles and classroom enactment; and (4) structured return paths through which synchronous decisions re-entered asynchronous spaces for individual refinement and community validation. These mechanisms collectively explain how a bichronous model can help teachers maintain pedagogical integrity even when external constraints threaten core learning goals, suggesting that bichronous PD cultivates not only knowledge but also professional resilience under uncertainty.

Design Principles, Adaptation, and Future Directions

This study yields three core orchestration principles for future oTPD design that emphasize integration over isolation. First, practitioners should coordinate modalities via visible feedback loops rather than treating them as parallel activities; the program's success relied on handoffs where asynchronous uncertainties directly shaped synchronous agendas, while synchronous decisions were pushed back into forums for final refinement. Second, the archive must be treated as a pedagogical seed rather than a static repository, necessitating a searchable, community-authored library where the resurfacing of past threads maintains continuity throughout the PD lifecycle. Finally, designers must optimize for complementary affordances by assigning distinct instructional functions to each space (i.e., reserving asynchronous environments for depth and curation, while utilizing synchronous sessions for real-time clarification and collaborative problem-solving). Although the present study examined a small, well-resourced cohort in the Northeastern United States, adapting these principles to other contexts is possible through deliberate redesign of technological infrastructure that can incorporate institutional and resource conditions associated with larger scales of teacher participants.

In technology-constrained environments, the synchronous component as implemented in this study would likely be infeasible, but the underlying coordination logic can be preserved through lower-bandwidth substitutes. The critical

design requirement is the preservation of the handoff between modalities. A facilitator must still be able to identify uncertainties surfacing in delayed exchanges and route them into a real-time channel, and decisions made in real-time must still re-enter the asynchronous space for refinement. Live video sessions could be replaced with audio-only conferencing, scheduled voice calls, or moderated mobile-messaging sessions that retain the immediacy function of synchronous interaction without requiring sustained video streaming. Asynchronous discussion forums, similarly, could be hosted on lightweight mobile platforms or even structured messaging groups rather than a full MOOC platform.

Larger cohorts introduce a different set of design pressures. The tiered reply structure depends on participants being able to follow and contribute to a manageable number of threads. As cohort size grows, whole-group forums tend to fragment attention and reduce the likelihood that any single thread accumulates the sustained, multi-level dialogue observed in this study. Scaling the model would require structural modifications such as small-group cohort pods similar in size to this study operating in parallel with periodic cross-pod synchronous sessions for shared expert input. Facilitator capacity would likewise need to scale since the diagnostic use of forum data to shape live agendas becomes infeasible for a small facilitator team beyond a certain cohort size. Distributed facilitation across multiple trained co-facilitators or AI-assisted thread digesting tools offer alternative options for sustaining this coordination function at scale.

In less-resourced contexts, adaptation requires attention to multiple factors including technology, teacher workload, language of instruction, the availability of subject matter experts in emerging STEM fields, and institutional norms around PD. The model's reliance on subject matter experts to provide theoretical scaffolding presumes access to such experts which may be limited in settings where bioinformatics or comparable interdisciplinary domains are still establishing institutional presence. In these contexts, the model could be adapted by building regional or international expert networks that rotate across multiple PD cohorts, by leveraging asynchronous expert contributions to reduce dependence on real-time expert availability, and by positioning experienced teachers from prior cohorts as primary facilitators once an initial cohort has been trained. The teacher facilitator role observed in the study offers a transferable mechanism for distributing expertise across cohorts without requiring continuous involvement of external specialists. Across all three adaptation contexts, the consistent design principle is that the bichronous model is defined by the coordination mechanisms rather than by the specific platforms or cohort composition. Practitioners adapting the model should preserve the four mechanisms while substituting context-appropriate technologies, group structures, and expertise arrangements.

Several limitations warrant attention. First, the PLC involved nine purposefully recruited, highly motivated teachers within a specific program and institutional context, and the COVID-19 pandemic likely amplified the value of collective problem-solving in ways that may be partially situational; future research should investigate how these coordination mechanisms function across larger, more heterogeneous PLCs, different STEM disciplines, and non-pandemic conditions. Second, as an exploratory qualitative study designed to identify emergent patterns rather than

quantify outcomes, the findings represent themes derived from consistent trends across the majority of the data rather than statistically measured effects; future work should incorporate mixed-methods and quasi-experimental designs including discourse analytics, learning analytics, and pre-post CK/PCK assessments to quantify which coordination mechanisms contribute most to teacher learning. Third, the study documents teachers' developing professional discourse and implementation plans but does not trace these to enacted classroom practice or student outcomes; longitudinal studies should follow teachers from PD through instruction using observation protocols and student achievement data. Additionally, the coordination mechanisms identified here, particularly facilitator use of forum data and resurfacing of archived resources, suggest promising sites for AI augmentation through tools that generate thread digests or flag unresolved questions, which should be evaluated for their impact on facilitator responsiveness and the preservation of context-rich professional dialogue.

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