Co-Designing AI-Based Orchestration Tools to Support Dynamic Transitions: Design Narratives Through Conjecture Mapping

LuEttaMae Lawrence, University of California, Irvine, luettamaelawrence@gmail.com
Boyuan Guo, Carnegie Mellon University, boyuang@andrew.cmu.edu
Kexin Yang, Carnegie Mellon University, kexiny@andrew.cmu.edu
Vanessa Echeverria, Escuela Superior Politécnica del Litoral, vanechev@gmail.com
Zimmy Kang, Carnegie Mellon University, zimmyk@andrew.cmu.edu
Vikrant Bathala, Georgia Tech, vkbathala@outlook.com
Christina Li, Carnegie Mellon University, ckli2@andrew.cmu.edu
William Huang, Carnegie Mellon University, whuang3@andrew.cmu.edu
Vincent Aleven, Carnegie Mellon University, aleven@cs.cmu.edu
Nikol Rummel, Ruhr-University Bochum, nikol.rummel@rub.de

Abstract: Dynamically transitioning between individual and collaborative learning has been hypothesized to have positive effects, such as providing the optimal learning mode based on students' needs. There are, however, challenges in orchestrating these transitions in real-time while managing a classroom of students. AI-based orchestration tools have the potential to alleviate some of the orchestration load for teachers. In this study, we describe a sequence of three design sessions with teachers where we refine prototypes of an orchestration tool to support dynamic transitions. We leverage design narratives and conjecture mapping for the design of our novel orchestration tool. Our contributions include the orchestration tool itself; a description of how novel tool features were revised throughout the sessions with teachers, including *shared control between teachers, students, and AI* and the *use of AI to support dynamic transitions*, and a reflection of the changes to our design and theoretical conjectures.

Introduction

Like many design-based research projects, our goal is to design technology to be used in classroom contexts. However, before moving to the classroom to evaluate our design, we focus our attention on the design process. Often in the CSCL community, researchers focus on what is created rather than how (Kali, 2016). In this paper, we focus on how teachers adapt our design through the lens of conjecture mapping (Sandoval, 2014). We present a sequence of design sessions that resulted in a novel AI-based orchestration tool to support dynamic transitions between individual and collaborative learning, described in detail below. Conjecture mapping helped us to describe the novel features of the tool, including *shared control between teachers, students, and AI* and the *use of AI to support dynamic transitions*, and share reflections of the theoretically conjectures about dynamic transitions.

Perspectives

Dynamic Transitions

Individual and collaborative learning have different strengths, such that they support different types of knowledge and, thus, are relevant at different times in the learning process (Mullins et al., 2011). Research has shown that combining individual and collaborative learning can be more effective than using either alone (Olsen et al., 2019). Therefore, one potential way to support students and benefit from both models of learning is to let them switch dynamically between the two (Olsen et al., 2021). Prompting one student to help another can improve individual accountability, peer interactions, and positive interdependence among peers (Manathunga & Hernandez-Leo, 2019). To orchestrate dynamic transitions, the teacher needs to pair and unpair students in a needs-tailored fashion. Such transitions do naturally occur in classrooms, including instances where one student helps another without prompt (Ogan et al., 2012) or teachers ask one student to help another (Holstein et al., 2020).

While transitions can occur naturally, orchestrating dynamic transitions in real-time implies a range of complex activities for teachers. Transitions require detecting students who may need help, identifying the best pairs according to students' state of learning and the learning activity, selecting and initiating the peer tutoring activity, and simultaneously monitoring both individual and collaborative progress. Orchestrating activities across learning modes can place a heavy load on the teachers, especially in real-time (Roschelle et al., 2013). While previous literature has created tools to support dynamic transitions between learning modes (Tissenbaum & Slotta, 2019), little is known about how AI can support such transitions.

We explore the design of an AI-based tool to help teachers orchestrate transitions between individual and collaborative learning. The goal of this novel tool is to incorporate data from students' use of our individual and collaborative AI-based tutoring systems to assist teachers in identifying when and why dynamic transitions may be necessary and aid in facilitation. We have explored the feasibility of orchestrating dynamic transitions across students, teachers, and AI in real classrooms, and found teachers want to share control of this process, as managing these activities alone is too much (Echeverria et al., 2020). Follow-up studies investigated the role of shared control and found teachers want the AI to provide suggestions and explanations to identify when and why transitions may be necessary (Yang et al., 2021a). We extend these findings by operationalizing the design recommendations in the form of prototypes we refine through co-design sessions with teachers.

Design Narratives and Conjecture Mapping

Given the complex nature of dynamically transitioning between learning modes, the design of tools should be aligned with the existing practices of teachers. We enacted co-design to integrate teacher input to ensure the AI support aligns with their needs and context. Co-design has been used to create technologies that support teachers' pedagogy and student collaboration (Lawrence & Mercier, 2019; Holstein et al., 2019; Martinez-Maldonado et al., 2019; Tissenbaum & Slotta, 2019). To ensure CSCL technologies are sustainable, researchers recommend co-creating technologies that make learning visible through learning analytics and promote agency in the process (Law et al., 2021). Providing teachers with this agency over what is designed, shifts authority, and enables them to shape the technology to ensure it fits the needs of their.

In the CSCL community, design narratives have been used to illustrate the realities of co-design, make contributions to how systems are created to support collaboration, and uncover insights through iteration (Hoadley, 2002). One method used to illustrate the design narratives is through conjecture mapping, a tool used to conceptualize how learning designs are theoretically grounded and articulate hypotheses about designs (Sandoval, 2014). Conjecture mapping (see example in Figure 1) first makes explicit a high-level conjecture, or a theoretical idea about the learning and context. *Embodiment* refers to the features of the learning design, including *tools, tasks, participant structures,* and *discursive practices*. The *embodiment* features are hypothesized to generate *mediated processes* (interactions), also known as the *design conjecture*. The *theoretical conjecture* is the hypothesized interaction between the *mediated processes* and the *outcomes*. Sandoval (2014) argues that design features do not directly lead to learning outcomes, but it is the interactions that emerge while using a designed tool that impact learning outcomes. Therefore, we make *design conjectures*, which explain how designs (*embodiment*) generate interactions (*mediated processes*), and *theoretical conjectures*, which explain how these processes generate learning *outcomes*. In this paper, we leverage conjecture mapping (Sandoval, 2014) and design narratives (Hoadley, 2002) as our analytic approach to explore how our *design and theoretical conjectures* about dynamic transitions were informed by teachers' insights.

Methods

Learning Context

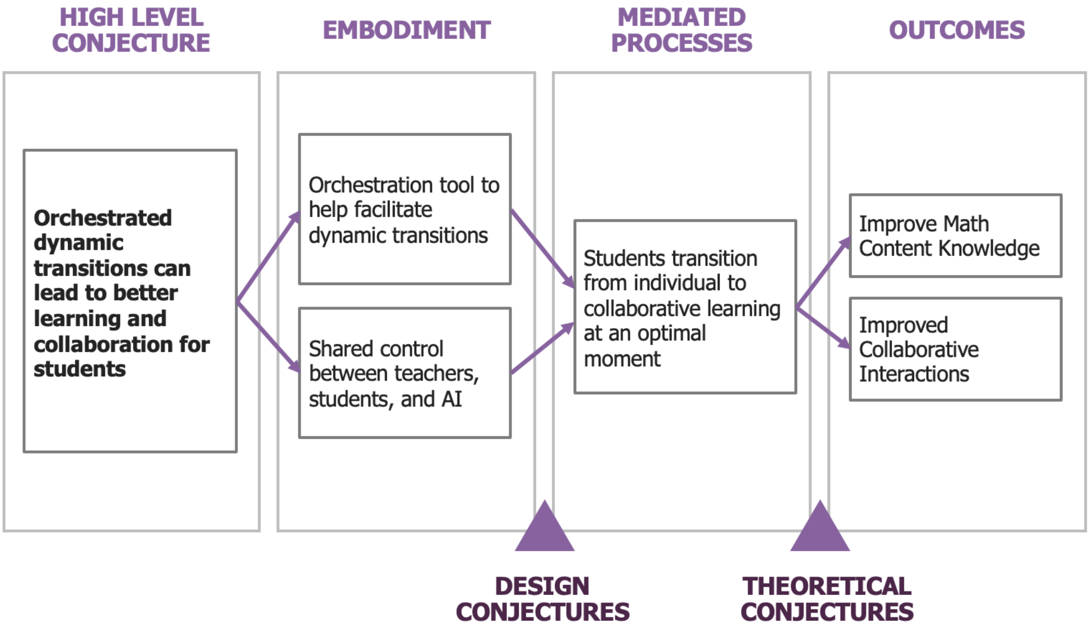
This study reports on three design sessions with unique activities aimed at creating a dynamic pairing orchestration tool with shared control between teachers, students, and AI. The orchestration tool is positioned in the context of two AI-based tutoring systems, *Lynette*, an individual problem-solving tutoring system, and *APTA*, a collaborative tutoring system that provides a space for mutual peer tutoring. Both tools are used to teach linear equation solving for middle school students and have been shown to improve learning (Walker et al., 2014). While these tools are typically used separately, we have explored the feasibility of using the two tools to support dynamic switching (Echeverria et al., 2020).

Figure 1 shows our research team's initial conjecture map, of the *design* and *theoretical* conjectures prior to our design process. The embodied features of the orchestration tool are for teachers, students, and AI to co-orchestrate dynamic transitions through a learning dashboard. Through interaction with the orchestration tool and participant structures, students can transition from individual to collaborative tasks at the optimal moment in their learning process (*design conjecture*). We hypothesize that these transitions will support our intended learning outcomes to improve mathematics content knowledge and collaborative interactions (*theoretical conjecture*). Our initial conjecture map was created leveraging previous user research insights from both teacher and student perspectives (Echeverria et al., 2020; Yang et al., 2021a).

Participants

Twelve middle school math teachers (10 females) participated in the three design sessions. Due to varying availability, four teachers participated in all three sessions, three teachers participated in two sessions and the remaining five participated in one session. Each teacher consented to take part in the research and was compensated with a $30 Amazon gift card for each session they participated in.

Figure 1. Conjecture map before the design process.



Data Collection

To provide a thick description of our design process and prototypes (Hoadley, 2002), we used a range of data sources (Table 1). We conducted three sessions; each one had a specific focus and co-design activity–described in more detail below. All sessions were conducted virtually with one teacher at a time and recorded through a video conferencing platform. In total, we had approximately 21 hours of video data, which were transcribed using an online transcription service. During each session, we collected observation notes and documented artifacts and prototypes. After each session, the research team met to synthesize insights and made decisions about the prototypes, resulting in notes and slide decks of findings that were used in the subsequent session.

Table 1. Data collection by design session.

Design Activities	Teachers	Video	Observations	Prototypes	Meetings
Co-constructing low-fidelity prototypes (Session 1)	7	7 1-hr videos	35 pages of notes	7 Google Slides prototypes	8 pages notes
Iterative prototype feedback (Session 2)	8	8 1-hr videos	44 pages of notes	8 Figma prototypes	12 slides; 11 pages of notes
Interactive user testing (Session 3)	3	3 1-hr videos	13 pages of notes	1 interactive prototype	11 slides; 4 pages of notes

Analysis

We analyzed session recordings using Affinity Diagramming, a design method for clustering and re-clustering quotes to identify themes (Martin & Hanington, 2012). Two members of the research team reviewed the videos, transcripts, observation notes, and prototypes from sessions to separate design ideas into data points. During clustering, we continuously returned to the data to ensure we were capturing the context. We generated first-round codes, building on findings from past research on the open design challenges identified from previous research on orchestrating dynamic transitions, including *timeliness of pairs*, *teachers' desire for control and awareness,* and *dynamics between parties with shared control* (Yang et al. 2021). Between each session, two coders iteratively developed themes. Agreement was established by internal meetings of the research team to make decisions about the next steps based on emergent themes. We used memoing to summarize the main ideas of the design sessions to promote reflexivity and document our design and theoretical decisions throughout the design process (Birks et al., 2008). Memos highlighted our assumptions and design decisions. We reconstructed them into the design narratives presented in this paper reflecting on the design and theoretical conjectures.

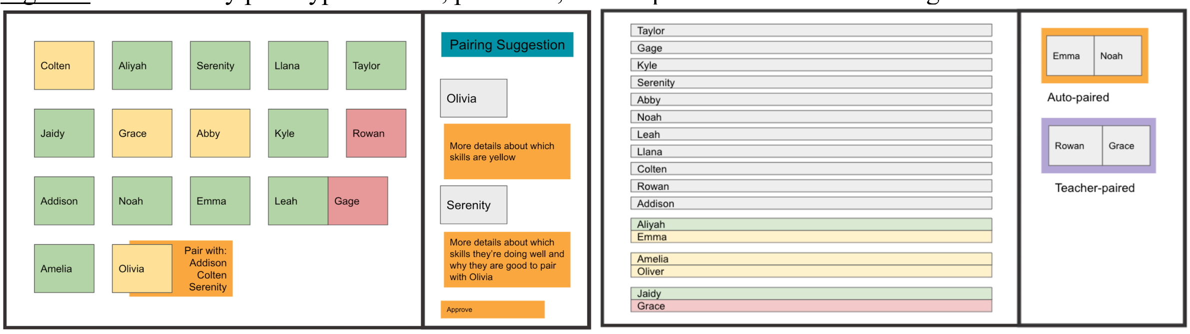
Design Narratives

In this section, we describe the co-design session to build the prototypes through design narratives. Sessions were in sequence, meaning findings from session one were used to inform prototypes in session two, and so forth. For each design session, we describe the *session activity* including activity and prototype details, and *findings*.

Design session 1: Co-constructing prototypes

Session activity. The goal of the first design session was to refine low-fidelity prototypes (Buchenau & Suri, 2000) of the orchestration tool. First, we asked teachers to comment, and generate additional prototypes or ideas based on what was presented and how they might pair their students (Figure 2). Prototypes were presented in Google Slides and used their students' first names (provided by each teacher) to add realism to the pairing process. Finally, we asked teachers to reflect on the prototype they thought was most useful by asking probing questions to investigate if the design met their needs and learning context. The primary affordance of the prototypes was high-level information about students, who are using a tutoring software that documents students' interactions, and potential interactions for teachers to imagine how they might pair students dynamically. The prototypes were created using insights from previous user studies (Echeverria et al., 2020; Yang et al., 2021a; Yang et al., 2021b). We proposed multiple methods for pairing interaction, shared designs for how data might be presented, and probed about how AI might support these learning transitions.

Figure 2. Low-fidelity prototypes created, presented, and adapted with teachers in Google Slides.



Findings. Teachers validated our *theoretical conjecture* – dynamic transitions are a way to support students' mathematics knowledge and collaboration skills. Yet, there were tensions regarding the *participant structures* or teachers' shared control over these transitions with students and the AI. Teachers shared pairing suggestions from the AI could be helpful, but they felt they themselves better understood students' learning needs and the factors in the classroom that impact collaboration. Regarding shared control with students, many teachers felt it could be overwhelming to get suggestions from students. Teachers shared that students should not be able to deny pairings, because they needed to learn to work with different people. One teacher described, "*Most of them will deny pairs [if given the option]. So, we will be there, like going back to the drawing board and won't make any progress in class. So, I prefer, like the teacher should have the final decision.*" There was a consensus over teachers having the final say regardless of who is making suggestions but preferred AI suggestions.

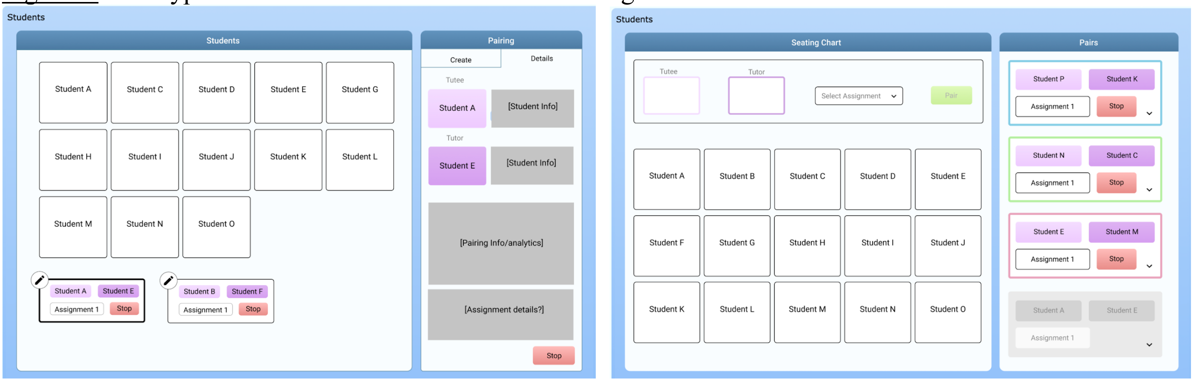
We presented teachers with several options for how data about pairings might appear (e.g., glanceable icons, listed data, pop-ups, side panels, combinations). There was consensus toward combinations of designs that afforded teachers' the awareness and orchestration of all the learning processes simultaneously, for instance, monitoring all students working individually and collaboratively, while also making and approving pairing and unpairing suggestions. Teachers wanted options rather than one possible pairing. For instance, if there are issues between two students, the teacher could simply choose another pair without starting the pairing process over.

Design session 2: Iterative prototype feedback

Session activity

The goal of the second design session was to refine prototypes of the orchestration tool. We shared a series of mid-fidelity prototypes for teachers to provide feedback (Figure 3). Prototypes were constructed based on insights from the previous session and included the first name of students in their class to provide realism. Prototypes were presented through screen sharing in Figma. Figma was used to simulate interaction; however, prototypes were not fully functional. Throughout the session, the researchers presented each prototype and asked for feedback. The main affordance of the prototypes was to support co-orchestration between teachers and AI about dynamic transitions that allowed teachers to retain their agency and awareness of the learning process (*participant structure*). We created prototypes that focused on the interactions between the teachers and the AI and shared data about students learning, including AI making suggestions through drop downs or side panels, AI sharing data to describe pairing or unpairing suggestions, and additional features for teachers to stop pairings, and monitor and view data about both modes of learning.

Figure 3. Prototypes of the orchestration tool created in Figma.



Findings

One key insight that emerged was that the format and type of the data (*tool feature*) that teachers wanted, differed based on the moments in the dynamic transitions process (*mediated processes*) and their learning goals (*outcomes*). Teachers wanted *quick*, *scannable data* of the whole class to monitor how both individual and collaborative learning was going (e.g., productive, struggling, needs help). Due to the high orchestration load of dynamic transitions, teachers felt too much information was hard to parse and act on at the moment (*design conjecture*). Teachers wanted to be able to *manually request more detailed data* when they were making a pairing, evaluating a suggested pairing, or wanted more information about an individual or collaborative pair.

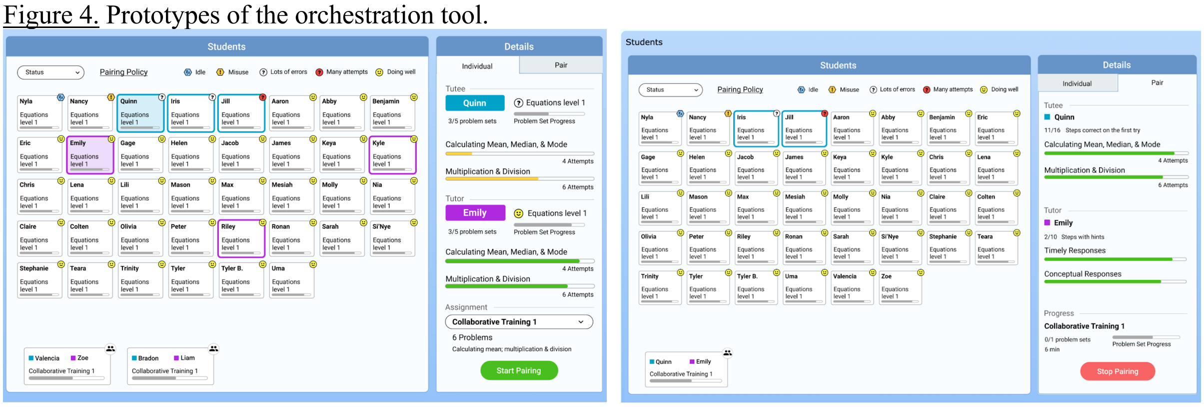
A theme that came up several times was the option to customize data in the orchestration tool (*design conjecture*) depending on the learning goals (*theoretical conjecture*). One teacher explained, "*I would want to be able to choose what I want to look at. But all of those [data] could be useful, depending on what I want to do. Like what my purpose is, like?*" She elaborated that if the collaborative learning goal was to support content learning, the desired data would differ compared to if her goal is to support their collaborative interactions. Customization, a *tool feature*, came up with several teachers. It, however, also created tension for the research team. While this level of flexibility was desired by teachers, the technical need to support customization requires significant infrastructure beyond the existing system. Therefore, we evaluated what design features and interactions might be most useful (*design conjectures*) when teachers are managing multiple learning goals (*theoretical conjecture*). These features included: (1) view of the whole class (e.g., students' current state, task they are working on, progress through the tasks), (2) suggestions from the AI for potential partners for a student, (3) explanations for why a student as suggested (e.g., comparison between the two students), (4) additional information about the students (e.g., deep dive with more data), and (5) explanations behind the algorithm. Teachers described the need for the data in the system to support their awareness of ongoing collaborative and individual tasks but also understand the justifications behind the AI's suggestions, helping it seem less like a black box and prompt more trust through the features described above.

Design session 3: Interactive user testing

Session activity

In the final design session, we did interactive user testing with teachers (Buchenau & Suri, 2000). To simulate how the tool might work in context, we tested out a fully functioning prototype of the orchestration tool. Three teachers took part in these sessions; all had taken part in the previous two sessions, meaning they had robust knowledge of the system. One member of the research team shared their screen and, through the video conferencing system, gave remote access to the teacher so they could interact with the orchestration tool. We then prompted the teacher to think aloud while pairing their students (Jaspers et al., 2004). The primary affordance of the tool focused on how teachers might get support from the AI but still have agency and awareness in the process (*design conjecture*). Features were designed and refined in previous sessions to support math content knowledge and collaborative interactions for students (*theoretical conjecture*). Based on the prototype feedback, we made changes to the *tool features* so that teachers could monitor and request data about students' individual and collaborative learning processes. While we decided customization was not feasible in this iteration of the tool, deep dives provide more data which gives teachers the agency to see additional or different data depending on their need in the moment. The *participant structures* made it possible for teachers to make pairings on their own or from suggestions made by the AI. Additionally, we added a feature that provides an explanation of the algorithm that was used to make suggestions.

Figure 4. Prototypes of the orchestration tool.



Findings. The interactive user testing allowed teachers to test interaction sequences that, in previous sessions, the researchers had control over. From the think-aloud, teachers reacted positively to data presented about the whole class, to explain pairing and unpairing suggestions, and to understand how students were doing in individual and collaborative tasks. Teachers described that the use of icons, bar graphs, and labels (see Figure 4) was helpful to understand what was happening quickly while also attending to ongoing activities in the classroom, rather than reading through lots of data and descriptions. The new *tool feature* embedded, that had not been previously discussed, was the explanations of the algorithm, and was liked by all three teachers. This feature also prompted further discussion about customization. Teachers expressed wanting to choose what algorithm could be used (*embodiment*), based on the learning goals they were trying to achieve during the lesson (*outcome*). Feedback from the think-aloud helped the research team polish language for labels in the system and refine color coding and size of text to add clarity to the sequence of dynamic pairing interactions.

Conclusions and Implications

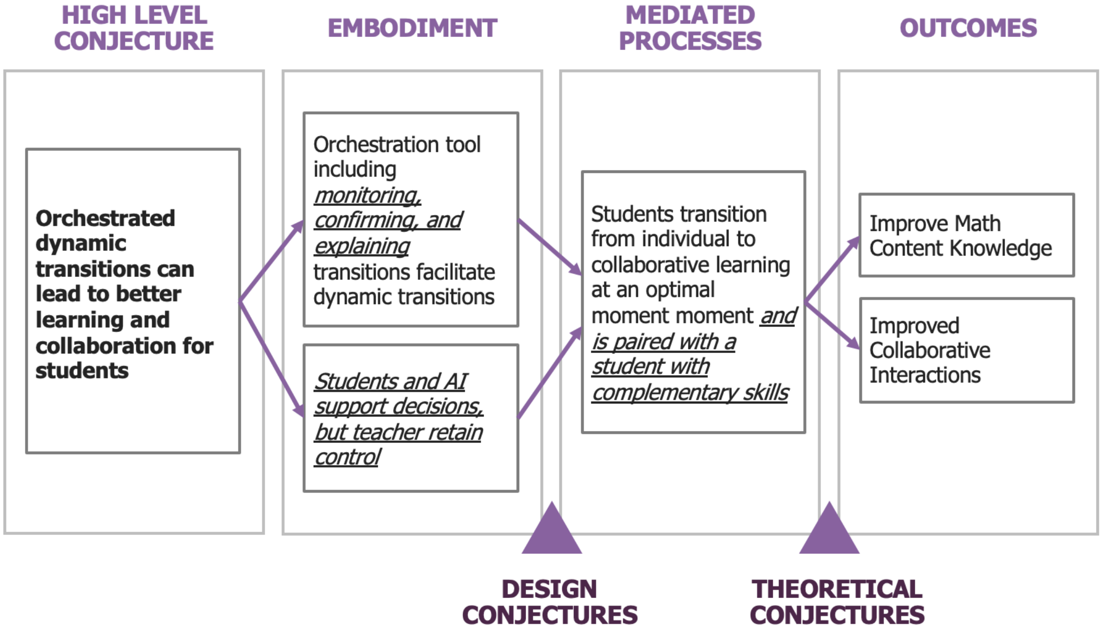
Refining our Conjecture Map Based on Teacher Insights

We made several changes to our conjecture map throughout the design sessions (Figure 5). First, we refined the *embodiment features*, including the *tool features* and the *participant structures.* Teachers desired tool features including data for monitoring, confirmation of pairing suggestions to retain control over transitions, and explanation of pairing and unpairing suggestions. Our initial *participant structures* outlined the need to share control between students, AI, and teachers. Teachers expanded this definition to include dynamics in their classrooms. They wanted suggestions from the AI, but not students, and needed to have the final say. Teachers felt they themselves have a better understanding of students' personal needs and contextual factors in the classroom that they felt impact collaboration.

Teachers expanded our *mediated processes* to include the need to pair students with someone who is going to be able to support them. To support our *design conjecture,* we made intentional decisions in the *tool* based on insights from teachers to help them understand why two students might work well together. For instance, teachers wanted the AI to help monitor students' performance and give suggestions, but wanted data, including skill level, progress on individual tasks, and past collaborations, to compare students, understand why they were suggested, and confirm the AIs recommendation. While our *design conjecture* focused on how to help teachers interpret the optimal moment to transition between individual and collaborative learning, our *theoretical conjecture* hypothesized what those optimal moments are for transitioning that will impact students' mathematics content knowledge and collaboration skills. Teachers helped us refine this conjecture by elaborating that students need to be paired when it is necessary for their learning process, but also that they need to be paired with someone who has complementary skills. Teachers explained that measuring these skills should be informed by the AI's knowledge of students' learning interactions and the teachers' knowledge of the social factors in the classroom.

The novelty of our AI-based orchestration tool lies in the shared control across parties (*participant structure*) and the use of algorithms to identify moments where collaborative learning may be beneficial for students (*tool feature*). Conjecture mapping enabled us to reflect on how our initial hypotheses about these features were revised based on teachers' feedback. We initially aimed to create a tool that distributed control of dynamic transitions across students, teachers, and AI, yet throughout the design sessions, teachers were hesitant about sharing control with students. In the current tool, we focused on shared control between teachers and AI, with future work exploring features to give students agency while accounting for teachers' needs. Exploring the novel use of AI to support dynamic transitions with teachers, allowed us to understand the features necessary to make teachers comfortable with suggestions from an algorithm, including sharing explanations while retaining their agency in the final decision. These nuanced design features are important because how we design the tool will affect the *mediated processes* that emerge in the classroom, in turn impacting the hypothesized outcomes.

Figure 5. Map of conjectures produced after the design process.



Future Work and Implications

The three design sessions presented above illustrate how we designed the orchestration tool based on the rich data we gathered from interactions with teachers, coupled with theoretical insights on supporting dynamic transitions. We focused on the *design* and *theoretical conjectures* about supporting dynamic transitions, but, due to space limitation, did not cover the optimal moments for dynamic transitions in this paper (see Yang et al., 2021a). Our ongoing work is exploring when students may need to transition from individual to collaborative learning. The next step in our design sequence is to run a classroom pilot to evaluate the *design* and *theoretical conjectures*.

The goal of this paper was to describe a sequence of rich design sessions that resulted in a novel AI-based orchestration tool; however, we also recognize the use of conjecture mapping as a lens to reflect on dynamic transitions as a pedagogical approach. Pairing conjecture mapping (Sandoval, 2014) and rich narratives (Hoadley, 2002) enabled us to reflect on how our conjectures about dynamic transitions changed, to inform how we study them moving forward. While these findings result in a context-specific orchestration tool and designs for our future work, we believe this analysis lays the groundwork for other researchers creating similar technologies to support collaborative learning.

References

Birks, M., Chapman, Y., & Francis, K. (2008). Memoing in qualitative research: Probing data and processes. *Journal of Research in Nursing*, *13*(1), 68

Buchenau, M., & Suri, J. F. (2000, August). Experience prototyping. In *Proceedings of the 3rd Conference on Designing interactive systems: Processes, practices, methods, and techniques* (pp. 424-433).

Echeverria, V., Holstein, K., Huang, J., Sewall, J., Rummel, N., & Aleven, V. (2020, September). Exploring human–AI control over dynamic transitions between individual and collaborative learning. In *European Conference on Technology Enhanced Learning* (pp. 230-243). Springer, Cham.

Hoadley, C. (2002). Creating context: Design-based research in creating and understanding CSCL. In *CSCL '02: Proceedings of the Conference on Computer Support for Collaborative Learning: Foundations for a CSCL Community*, 453–462.

Holstein, K., McLaren, B. M., & Aleven, V. (2019). Co-designing a real-time classroom orchestration tool to support teacher–AI complementarity. *Journal of Learning Analytics*, *6*(2).

Jaspers, M. W., Steen, T., Van Den Bos, C., & Geenen, M. (2004). The think aloud method: a guide to user interface design. *International Journal of Medical Informatics*, *73*(11-12), 781-795.

Kaendler, C., Wiedmann, M., Rummel, N., & Spada, H. (2015). Teacher competencies for the implementation of collaborative learning in the classroom: A framework and research review. *Educational Psychology Review*, *27*(3), 505-536.

Kali, Y. (2016). Transformative learning in design research: The story behind the scenes. In *Transforming Learning, Empowering Learners, the International Conference of the Learning Sciences (ICLS)* (Vol. 1, pp. 4-5).

Law, N., Zhang, J., & Peppler, K. (2021). Sustainability and scalability of CSCL innovations. In *International Handbook of Computer-Supported Collaborative Learning* (pp. 121-141). Springer, Cham.

Lawrence, L. & Mercier, E. (2019). Co-design of an orchestration tool: Supporting engineering teaching assistants as they facilitate collaborative learning. *Interaction Design and Architecture(s) Journal,* (42), 111- 130.

Manathunga, K., & Hernández-Leo, D. (2019). Flexible CSCL orchestration technology: Mechanisms for elasticity and dynamism in pyramid script flows. In *the International Conference of the Learning Sciences (ICLS)* (pp. 248-256).

Martin, B., Hanington, B., & Hanington, B. M. (2012). Universal methods of design: 100 ways to research complex problems. *Develop Innovative Ideas, and Design Effective Solutions*, 12-13.

Martinez-Maldonado, R., Echeverria, V., Elliott, D., Axisa, C., Power, T., & Shum, S. B. (2019). Making the design of CSCL analytics interfaces a co-design process: The case of multimodal teamwork in healthcare. In *CSCL 2019: Proceedings of the Conference on Computer Support for Collaborative Learning.*

Mullins, D., Rummel, N., & Spada, H. (2011). Are two heads always better than one? Differential effects of collaboration on students' computer-supported learning in mathematics. *International Journal of Computer-Supported Collaborative Learning*, *6*(3), 421-443.

Olsen, J. K., Rummel, N., & Aleven, V. (2019). It is not either or: An initial investigation into combining collaborative and individual learning using an ITS. *International Journal of Computer-Supported Collaborative Learning*, *14*(3), 353-381.

Olsen, J.K., Rummel, N., & Aleven, V. (2021). Designing for the co-orchestration of social transitions between individual, small-group and whole-class learning in the classroom. *International Journal of Artificial Intelligence in Education*, 31, 24-56.

Ogan, A., Walker, E., Baker, R. S., Rebolledo Mendez, G., Jimenez Castro, M., Laurentino, T., & De Carvalho, A. (2012, May). Collaboration in cognitive tutor use in Latin America: Field study and design recommendations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 1381-1390).

Roschelle, J., Dimitriadis, Y., & Hoppe, U. (2013). Classroom orchestration: Synthesis. *Computers & Education*, *69*, 523-526.

Sandoval, W. (2014). Conjecture mapping: An approach to systematic educational design research. *Journal of the learning sciences*, *23*(1), 18-36.

Tissenbaum, M., & Slotta, J. D. (2019). Developing a smart classroom infrastructure to support real-time student collaboration and inquiry: a 4-year design study. *Instructional Science*, *47*(4), 423-462.

Walker, E., Rummel, N., & Koedinger, K. R. (2014). Adaptive intelligent support to improve peer tutoring in algebra. *International Journal of Artificial Intelligence in Education*, *24*(1), 33-61.

Yang, K. B., Echeverria, V., Wang, X., Lawrence, L., Holstein, K., Rummel, N., & Aleven, V. (2021a). Exploring Policies for Dynamically Teaming up Students through Log Data Simulation. *International Educational Data Mining Society*.

Yang, K. B., Lawrence, L., Echeverria, V., Guo, B., Rummel, N., & Aleven, V. (2021b). Surveying Teachers' Preferences and Boundaries Regarding Human-AI Control in Dynamic Pairing of Students for Collaborative Learning. In *European Conference on Technology Enhanced Learning* (pp. 260-274).

Acknowledgements

This work was funded by the National Science Foundation (NSF) grant number 1822861. We also thank the teacher partners who worked with us throughout this project.