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Cross-community knowledge building with idea thread mapper

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Abstract

Research on computer-supported collaborative learning faces the challenge of extending student collaboration to higher social levels and enabling cross-boundary interaction. This study investigated collaborative knowledge building among four Grade 5 classroom communities that studied human body systems with the support of Idea Thread Mapper (ITM). While students in each classroom collaborated in their local (home) discourse space to investigate various human body functions, they generated reflective syntheses— "super notes"—to share knowledge progress and challenges in a cross-community meta-space. As a cross-community collaboration, students from the four classrooms further used the Super Talk feature of ITM to investigate a common problem: how do people grow? Data sources included classroom observations and videos, online discourse within each community, students' super notes and records of Super Talk discussion shared across the classrooms, and student interviews. The results showed that the fifth-graders were able to generate high quality super notes to reflect on their inquiry progress for cross-classroom sharing. Detailed analysis of the cross-classroom Super Talk documented students' multifaceted understanding constructed to understand how people grow, which built on the diverse ideas from each classroom and further contributed to enriching student discourse within each individual classroom. The findings are discussed focusing on how to approach cross-community collaboration as an expansive and dynamic context for high-level inquiry and continual knowledge building with technology support.

Key words: Boundary crossing · Cross-community collaboration · CSCL across social levels · Idea Thread Mapper · Knowledge Building

Introduction

In a rapidly changing world with social divides, global connectedness, and ever-emerging challenges, students need to learn to work creatively with diverse ideas and collaborate across boundaries to solve complex problems (OECD, 2018; Pendleton-Jullian & Brown 2018; Tan et al., 2021). Research on computer-supported collaborative learning (CSCL)

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sheds light on pedagogical models to engage students in collaborative problem solving and knowledge building, supported by new technology designs that provide shared spaces, interaction tools, and scaffolds for collaborative discourse (see Cress et al., 2021). To further expand CSCL research and leverage educational transformation, researchers call for efforts to investigate collaborative learning at higher social levels and over longer timescales (Chen et al., 2021; Stahl, 2013; Law et al., 2021; Wise & Schwarz, 2017). While most of our knowledge about CSCL is rooted in investigations of collaborative learning in small groups and individual classrooms, research in an expanded social context may uncover new learning mechanisms, design challenges and strategies for creating open configurations of creative knowledge practices.

The goal of the current study is to investigate how students pursue collaborative knowledge building in an expanded social context that involves cross-classroom collaboration. It is a difficult design challenge to support cross-classroom collaboration among young students. This research integrates pedagogical and technology innovations to support cross-classroom collaboration for knowledge building. Building on our prior studies (Yuan & Zhang, 2019; Zhang, Yuan, & Bogouslavsky, 2020), we test using a multi-layer interaction approach to organize knowledge building across a cluster of classrooms. While students in each classroom collaborate in their home space to investigate various problems, they share valuable insights and challenges in an online meta-space for cross-classroom sharing and discourse.

Below we first review the literature on the need to understand collaborative discourse across multiple social levels, which include small groups in each classroom community and cross-community collaboration. Building on the literature, we present a conceptual framework and technology design for supporting cross-community knowledge building, which is tested and elaborated through a design-based research study conducted in four Grade 5 classrooms.

Literature Review

The need for research to extend collaborative discourse across social levels

Educational innovations for a changing world emphasize cultivating collaborative discourse by which real-world knowledge communities solve complex problems and advance shared knowledge (Dunbar, 1997; Mercer & Littleton, 2007; Scardamalia, 2002; Slotta et al., 2014). Extensive research has investigated patterns of collaborative discourse, including the generation of progressively deeper questions, creation of explanations and theories, examination of ideas and hypotheses using evidence, constructive use of sources, mutual listening and idea coconstruction, and shared reflection on collective advances and personal contributions (e.g., Damşa 2014; Hmelo-Silver & Barrow, 2008; Järvelä et al., 2016; van Aalst, 2009). Through collaborative efforts, students not only refine their personal understanding but advance the state of their collective knowledge: to continually dig deeper, to develop multiple and broader views, and to “rise above” complex and messy information to formulate higher planes of understanding (Scardamalia, 2002). New problems and challenges emerge as the collaborative inquiry proceeds. Thus, students enact collective responsibility for co-monitoring the evolving inquiries and knowledge flows in their community in order to position their personal and collaborative efforts in productive ways. They need to know that expertise is allocated within and between communities and recognize themselves as part of a civilization-wide endeavor to advance the frontiers of knowledge (Scardamalia & Bereiter, 2006).

Collaborative discourse and interaction for knowledge building take place on different social levels, which represent different units of analysis. These include students' knowledge work as individuals, small groups, the community as a whole, and larger networks of communities. However, existing CSCL research tends to focus on a single unit of analysis in each study; most of the studies have focused on collaborative learning in small groups or in individual classrooms. To overcome this limitation, Stahl (2013) calls for research efforts to investigate collaborative learning across different social levels, ranging from individual learners to small groups and the larger community (institution). Such research may contribute new insights into how knowledge interacts and travels between the different units of analysis across different timescales, which are "crucially important for understanding and orchestrating learning in CSCL settings." (Stahl, 2013, p. 1). Echoing Stahl's call, researchers further recognize the need to support collaborative learning at scale, drawing upon social Web technologies (Cress et al., 2016). As Chen, Håklev, and Rosé (2021) highlight, collaborative learning at scale provides a prime opportunity to design for a larger audience and to make broader impacts. The expanded scale of collaborative learning may create an enriched context (knowledge asset) for learning; at the same time, it also brings about new design challenges with regards to increased information load, diverse learner needs, and complexity of learning interaction and process coordination.

Design for cross-community collaboration: Strategies and Challenges

Driven by the above-reviewed need, the current study investigates designs and processes of cross-classroom collaboration for scientific knowledge building in K-12 settings. Very few studies have explored cross-classroom collaboration among school-age children. Therefore, our literature review also considers research on collaborative learning at scale in broader contexts, including Massive Open Online Courses (MOOCs) in higher education and citizen science programs in informal learning settings.

Several design strategies have emerged to support students' collaborative interaction at a relatively large social scale. The first features *pooling*, which is to set up an open common space directly shared by all the participants who may come from different locations. This strategy is commonly used in MOOCs to support broad participation. A challenge arises pertaining to information overload, as students often find it overwhelming and confusing to navigate the large number of discussion posts accumulating over time (Hollands & Tirthali, 2014; McGuire, 2013). To deal with this challenge, researchers tested various strategies Li et al., 2014; Wen et al., 2017; Wise, Cui, & Vytasek, 2016), such as setting up sub-forums, tagging online posts based on sub-topics, or assigning students to smaller study groups either manually or automatically. While such strategies help reduce the complexity and scale of student interaction, future research needs to better harness the benefits of large-scale collaboration and allow students' ideas to be dynamically shared, organized, and further integrated as community knowledge resources (Chen et al., 2021).

The second design strategy features *cross-sharing* of local discussion spaces used by different groups of participants. For example, two studies explored cross-classroom collaboration for knowledge building using Knowledge Forum (Laferriere et al., 2012; Lai & Law, 2006). Students from different school sites had access to the discussion boards of their partner classrooms where they could directly read their online posts and respond. While such interactions were found beneficial for enriching student inquiry, understanding and reflection; the direct sharing of online forums between different classrooms also risks information overload. Students lack the time needed to read the large volume of online posts from different classrooms (in addition to the posts of their own classroom). Often it is also difficult to understand the online discourse of the other classrooms without knowing the context, such as what occurred in their face-to-face discussion and inquiry activities.

As the third strategy, researchers have started to test designs of collaborative spaces that involve *different layers* of interaction and knowledge representation. For example, to improve collaboration in MOOCs, Ferschke and colleagues (2015) integrated a layer of synchronous discussion on top of student asynchronous discussion in online forums. This additional layer allowed students to engage in collaborative reflection on difficult problems and form small ad-hoc study groups supported by a conversational agent. In research on citizen science programs aimed at enabling the broad participation of citizen volunteers in scientific practices, Huang and colleagues (2018) used an online platform to support the conversations in two community groups that engaged in collaborative investigations of local environmental issues. While the members of each group carried out collaborative inquiries and discussions, they developed a group mental model using a concept map to represent their collective understanding of the core environmental issues and factors. The co-created mental model was further used as a boundary object (Akkerman & Bakker, 2011) to support communication among citizen scientists, facilitators, and scientific communities. The studies above shed light on promising strategies to support cross-community interaction, including the co-creation and use of boundary objects. However, such strategies are yet to be fully developed and tested in school-based settings to support students' knowledge building across classroom communities.

Conceptual and design framework

To guide research on collaborative learning at higher social levels across classroom communities, we put forth a conceptual framework of cross-community knowledge building that leverages multi-layer interaction. This framework builds on insights gained from the broader fields, including social system views of creativity and knowledge creation (Csikszentmihalyi, 1999; Dunbar, 1997; Engeström, 2008; Latour & Woolgar, 1986; Sawyer, 2007), expansive learning that integrates horizontal moves across borders and vertical moves across levels (Engeström, 2014), and boundary crossing in communities of practice (Star & Griesemer, 1989; Wenger, 1998). Below we present our conceptual framing and then describe our technology design to support cross-community knowledge building.

Our conceptual framework considers cross-classroom knowledge building as a multilevel socio-ecological system that mirrors real-world knowledge production systems. Knowledge creation in the real world takes place in a multi-level socio-ecological system, in which individuals and teams conduct research in various domain areas while interacting with peers and ideas from the larger fields (Csikszentmihalyi, 1999). The social dialogue and interaction for knowledge building extend across different social levels: *Individuals* collaborate in *groups/teams* within each *organization/community*, which is further part of an *intellectual network (field)* that advances the collective knowledge of a domain (Csikszentmihalyi, 1999; Latour & Woolgar, 1986; Sawyer, 2007). A creative field leverages the work of different individuals and teams by accumulating a shared, easily-accessible knowledge base represented using various inscription systems (e.g., papers). The interaction between different research teams and areas enables dynamic contact and cross-fertilization of ideas (Sternberg, 2003), rendering a dynamic social context that shapes and sustains the work of individual teams and local communities.

Guided by the multi-level socio-ecological system view, we identified a set of design principles to approach collaborative knowledge building across classroom communities (Yuan & Zhang, 2019; Zhang et al., 2020). Firstly, we view cross-community interaction as a higher, emergent layer of collaborative discourse that builds on the ongoing local discourse within each classroom. Differing from the above-reviewed studies in which a large number of students share the same discussion forums or sub-forums, we adopt a multi-layer design that integrates the *local discourse spaces* of different communities with a *cross-community space* –or "meta-space" (Bereiter & Scardamalia, 2021)—for larger discourse. The interaction design allows information to flow between the two layers of discourse. The expanded discourse in the cross-classroom meta-space provides an expansive context for students to fuse and advance their ideas toward higher-level understandings. Research on real-world knowledge creation practices sheds light on how the different levels of discourse unfold (Dunbar, 1997; Latour & Woolgar, 1986). The local ongoing discourse within each research team tends to be more exploratory, incremental, and distributed (Dunbar, 1997), advancing ideas in the making. Members take "baby steps" to contribute and test diverse ideas and build on one another's input over time. Such interactive discourse may lead to new discoveries, theories, and solutions that cannot be attributed to any individual member's input. The larger discourse across different teams and communities focuses on negotiating major knowledge advances and connecting different expertise and perspectives to address complex challenges. To participate in the larger discourse, members of each team need to refine and transform their ideas toward higher epistemic levels in order to make valuable and accountable contributions to the field (Csikszentmihalyi, 1999; Latour & Woolgar, 1986). Similarly, designs of knowledge building among students should leverage the power of the different levels of discourse in a coherent manner in support of epistemic advances (Zhang, Tian, Yuan & Tao, 2022). Students in each classroom engage in interactive discourse to contribute and improve their ideas. As students transform their initial exploratory ideas toward more sophisticated understanding, they contribute their knowledge advances to the larger discourse for broader sharing and collaborative problem-solving.

Secondly, student interaction in the cross-community meta-space needs boundary-crossing support to make their knowledge work sharable and accessible. Thus, our approach leverages the power of boundary objects to represent and index student knowledge advances in each community. Objects generated by a community often have contextual meanings that are not easily accessible or transparent to other communities. "Boundary objects" have the potential to bridge the boundaries (discontinuities) between different communities in that they offer flexible "means of translation" (Star & Griesemer, 1989). They have a structure that is common enough to make them recognizable and interpretable across different social worlds, and at the same time, allow the participants to reinterpret and re-contextualize the meanings of the objects in a flexible manner in relation to their own practice. As noted earlier, raw online discussion entries posted by students over time are difficult to use as boundary objects to bridge different communities. As boundary objects, students in our research create metacognitive syntheses of productive lines of discourse and inquiry—which are called “super notes”—for cross-community sharing. Students read the super notes from partner classrooms to get a sense of their inquiry practices, including the unfolding directions, insights, and deeper challenges, forming the common ground for mutual learning and cross-community dialogue and collaboration.

Finally, designs for cross-classroom collaboration need to leverage dynamic idea contact and knowledge flows across multiple levels of discourse. In light of the literature on complex systems and social emergence (Sawyer, 2005), our design for multi-level knowledge building works with “the micro-macro link” across levels. The micro-macro link involves the bottom-up emergence of ideas from each group and community to the larger discourse space and the downward influence of the cross-community discourse on the future unfolding of inquiry and discourse in each community. Valuable ideas and problems developed in each community can travel up to the cross-community space for extended sharing and higher-level discourse. At the same time, knowledge and problems developed in the cross-community space may be brought back to each individual community to stimulate further inquiry and discourse and develop integrated understanding, taking into account the multiple perspectives from the different communities. Such idea interactions may provide a dynamic context for re-orchestrating different viewpoints, expertise, and inquiry practices of the various participants, stimulating expansive cycles of inquiry (Engeström, 2014) by which students connect their detailed knowledge of multiple components to build coherent understandings of the complex whole.

Table 1 The design of ITM to support cross-community knowledge building

Guiding principles	ITM features
(a) Social and epistemic emergence of ideas: Leverage the power of different levels of discourse and create a synergy between social uprising (emergence) and epistemic development of ideas.	- Multi-level collaboration to support within- and cross-classroom interaction. - Co-organization of high-potential areas for deep inquiry in each classroom. - Ongoing reflection on collective progress with analytics.
(b) Boundary crossing: Co-create epistemic boundary objects to synthesize emergent knowledge advances and support cross-boundary interaction.	- Co-authoring super notes using the Journey of Thinking reflection tool. - Sharing, searching, and reading super notes in the cross-community meta-space.
(c) Transformative idea interaction across levels: Support dynamic idea contact between different perspectives and knowledge flows across multiple levels of discourse to stimulate expansive cycles of inquiry.	- Ongoing access to the meta-space where different classrooms view one another’s inquiry organizer and super notes, which are further linked to threads of discourse. -Super Talk across buddy classrooms. - Notes (ideas) importing between the local and the shared meta-space.

Technology design

Enabling cross-community collaboration for knowledge building requires new technology innovations. As part of our multi-year design-based research, we have been testing the classroom processes and creating new technology support in response to the findings. In the early exploratory phase, we customized tools offered by Knowledge Forum (Scardamalia & Beretier, 2006) to support cross-classroom interaction. While each classroom worked on its own views (workspaces) in Knowledge Forum for focused discourse, a special view was set up for students to share super notes across classrooms. Findings from these explorations shed light on the classroom processes and challenges of cross-classroom interaction. Drawing upon the findings, our team (Zhang & Chen, 2019) created a multi-layer collaboration system: Idea Thread Mapper (ITM, http://idea-thread.net), which interoperates with Knowledge Forum. ITM integrates support for student-driven discourse in each community and boundary-crossing interaction across communities. The support for knowledge building within each classroom encourages emergent "reflective structuration" of inquiry by which students co-organize evolving inquiry directions and social roles as their collective work proceeds (Zhang et al., 2018). Systematic support is further incorporated to enable cross-

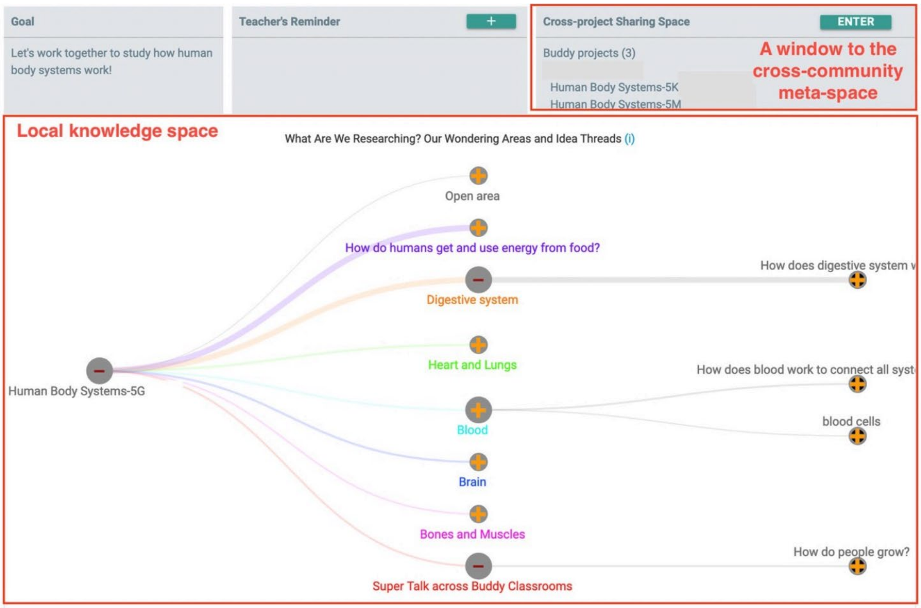

Fig. 1 The ITM homepage for each knowledge building initiative with a visual organizer of the local collaboration space and a cross-community space. The visual organizer shows the collective wondering areas and idea threads of a classroom. Each wondering area is a major direction of inquiry (e.g., blood in the human body inquiry) identified by the classroom members based on their interests and questions. Under each wondering area, members develop one or more inquiry threads, each of which investigates a more specific problem or challenge (e.g., how does blood work to connect all systems?). A student can select one or more wondering areas as a personal focus and adjust his/her focus as the inquiry unfolds. Students with shared interests form into spontaneous flexible groups

classroom sharing and collaboration. Table 1 summarizes ITM's design features for cross-community interaction corresponding to the above-presented conceptual principles.

Leverage the power of the different levels of discourse

ITM uses a multi-layer design to organize the collaborative online spaces. These include (a) the local space of each classroom where students conduct collaborative discourse and inquiry to advance their understanding of various problems, and (b) a cross-classroom meta-space where students view the inquiry directions of their partner classrooms, post/share super notes (syntheses), and engage in cross-classroom Super Talk focusing on challenging issues of common interest. The teacher can create "buddy connections" with other classrooms that are studying the same or related content areas. Such buddy connections can be created between different schools that use different Knowledge Forum/ITM servers and databases. Figure 1 shows the home (dashboard) page of a classroom's inquiry unit focused on human body systems. The center area shows this classroom's own inquiry addressing the various problems about the human body. The small window at the top provides a snapshot of the buddy classroom connections and shared Super Talk topics (see details below).

Within the local space of each classroom, ITM integrates the online discourse tools offered by Knowledge Forum. Students author/co-author notes and build on one another's notes in the interactive discourse. To enhance student epistemic reflection, ITM further incorporates a set of new features, including (a) visual tools (see Fig. 1) for students to co-organize high-potential "wondering areas" (inquiry areas) based on emergent questions and interests, and create specific "idea threads" (conceptual lines of discourse) to guide their collaborative discourse; (b) timeline-based mapping of collaborative discourse to support student reflection on collective progress; (c) a group-based reflection tool, Journey of

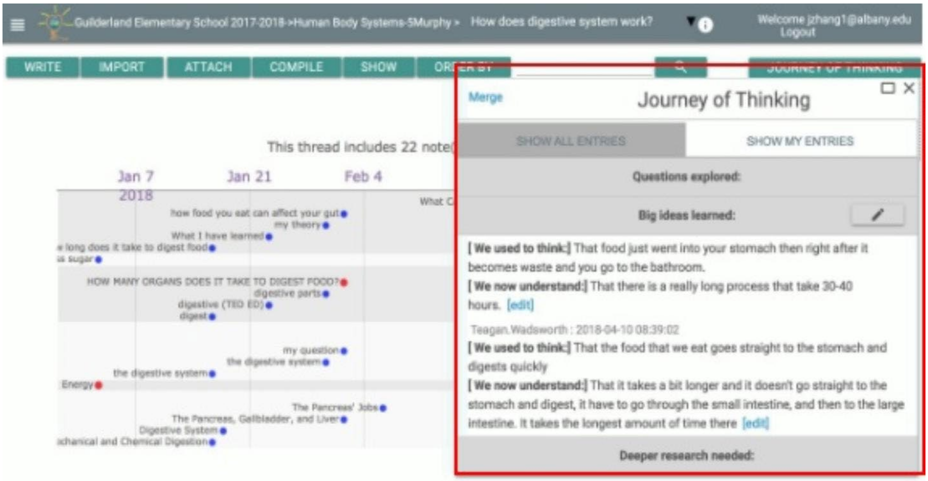

Fig. 2 A super note created using the Journey of Thinking (JoT) tool by a group of fifth graders to synthesize their online discourse on digestion. JoT includes three sections: problems/issues explored, "big ideas" learned so far, and deeper research needed. Scaffolds (sentence starters) are provided in each section to guide student reflection, such as using "We used to think…we now understand…" to reflect on new ideas learned

Thinking (JoT), with which students review their progress in each idea thread and co-author super notes (see details below); and (d) metacognitive analytics support including a topic modeling tool for students to identify emergent areas and directions of inquiry from their online discourse and automated feedback that assists student review of discourse contributions (Zhang et al., 2020).

Co-Create super notes as boundary objects

As students write and build on one another's notes to pursue a line of inquiry, they review the diverse idea contributions and synthesize their shared advances through co-authoring a super note using a reflection tool embedded in the discourse space: Journey of Thinking (JoT). Figure 2 shows a super note created by a group of fifth graders investigating how digestion works. As a common structure, their reflection was organized into three parts: questions explored, "big ideas" learned, and deeper research needed. Each section has a set of optional scaffolds (sentence starters), such as "We used to think…now we understand…" for reflecting on the transformative "big ideas" learned through the inquiry. Students who are involved in a line of inquiry (an idea thread) can co-author the super note by individually typing and then merging their reflective entries. The super notes from the various inquiry areas are automatically shared in the cross-community meta-space as boundary objects. Students can browse the super notes from partner classrooms or search for super notes most related to their interests.

Support idea interaction across communities and social levels

ITM gives students ongoing access to the cross-classroom meta-space where they can interact with peers and ideas from their buddy classrooms in various ways. They can access the super notes generated by peers from their buddy classrooms and find the most relevant syntheses based on the keyword index or using the search tool. They can get a holistic sense of what the buddy classrooms are working on by viewing the visual organizers of their won-

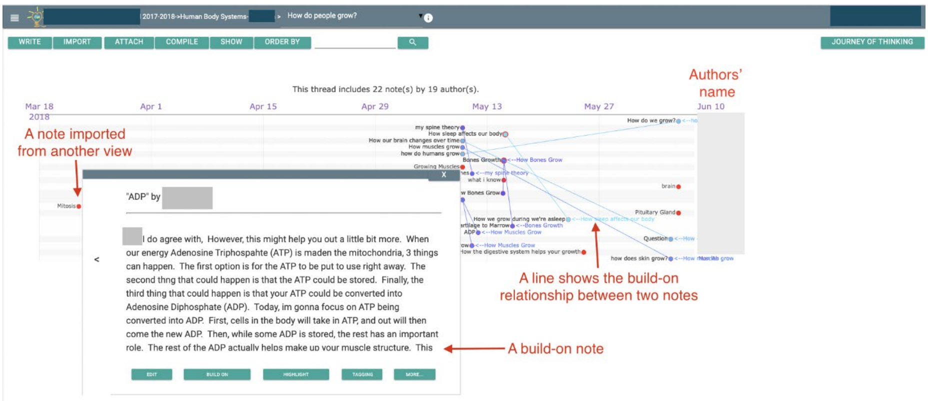

Fig. 3 The cross-classroom Super Talk about how people grow. Each dot represents a note posted by a student, and a line between two dots shows a build-on connection. Each note is positioned based on the date of creation (x-axis) and author (y-axis)

dering areas and idea threads, and, if interested, visit any of their idea threads to read the online discourse (in a read-only mode). For cross-classroom collaboration, students can also propose challenging issues as potential topics for cross-classroom joint discussion, which is called "Super Talk." The Super Talk topic, once approved by their teacher, will become a shared idea thread for cross-community discourse. Figure 3 shows an example topic about how people grow shared by a set of Grade 5 classrooms studying human body systems. There is a flexible function for importing notes that enables students to search and import notes (ideas) from their local discourse threads to the Super Talk for the larger discourse and *vice versa*.

The context and purpose of the current research

To test and refine the multi-layer emergent interaction approach to cross-community knowledge building, we conducted a series of design-based research (Collins et al., 2004) studies in a cluster of upper elementary science classrooms over several school years. While members of each classroom worked together to investigate various problems and deepen their understanding in their home discourse space, they identified productive lines of inquiry and generated super notes, which were accessible to the partner classrooms for boundary-crossing interaction and collaboration. The first two iterations (school years) in the design-based research tested cross-classroom collaboration support using Knowledge Forum, beginning with two grade 5/6 classrooms in the first iteration (Zhang et al., 2017, 2020) and expanding to a set of four parallel classrooms in the second iteration (Yuan & Zhang, 2019). The second iteration also included cross-year connection building; students had the chance to read the super notes created by the previous cohort group when studying the same curriculum topic. The findings suggest that the young students were able to recognize the dual-purpose of super notes: to formulate "big ideas" that rise above the diverse idea contributions of classroom members and enable broader, cross-boundary sharing of knowledge advances in an accountable and accessible manner. Motivated by the goal of producing knowledge advances for cross-community sharing, students engaged in intentional and collaborative efforts to improve their understanding toward higher epistemic levels. They generated super notes to consolidate their knowledge advances, capturing sophisticated scientific explanations and questions developed in productive areas of inquiry. Social network analysis of who had read whose super notes revealed intensive connections formed among the students within each classroom, between different classrooms, and across school years (student cohorts) (Yuan & Zhang, 2019; Zhang et al., 2020). The findings further suggest potential opportunities for such cross-community sharing to stimulate deeper inquiry within each classroom and collaborative dialogue across the partner classrooms. However, the above studies only explored this potential in a preliminary manner due to a lack of technical support and detailed tracing of students' idea interaction.

The current study, as the third iteration of this design-based research, investigated cross-community knowledge building at a deeper level, drawing upon the new technology support offered by ITM. As noted above, ITM integrates support for students' participation in their classroom-based discourse space and the shared meta-space. A set of features and tools support students' reflective structuring of inquiry directions and advances, ongoing writing and sharing of super notes co-authored using the Journey of Thinking tool, and collective Super

Talk across classrooms. Supported by ITM, the current study implemented a collaborative knowledge building initiative in four Grade 5 science classrooms that studied human body systems. In light of our multi-layer emergent interaction framework, this study aims to answer the following research questions: RQ1: How did students in each classroom develop collaborative inquiry to address core scientific issues of their interests? RQ2: In what ways did students compose their super notes to capture knowledge progress for cross-classroom sharing? RQ3: How did students initiate and participate in the cross-classroom Super Talk (as shown in Fig. 2), and with what knowledge advances? And RQ4: In what ways did the Super Talk discourse build on and further shape the knowledge work in each home classroom? RQ1 intends to provide a data-based account of student-generated inquiry and discourse within the home space of each classroom as the foundation for cross-classroom interaction. For the analysis of RQ2, we expect that ITM and the related classroom support would enable students to generate high-quality super notes reflecting on their knowledge progress in core topics of inquiry. RQ3 and RQ4 aim to produce a temporal view in the development of the cross-classroom discourse (i.e., how do people grow) and trace idea flow and connection between the different levels of discourse, from each home classroom to the cross-classroom Super Talk and back.

Method

Classroom settings and participants

This study was conducted in four Grade 5 classrooms at a public elementary school located in a suburban school district in the Northeastern U.S. The school enrolls approximately 550 students, 38.1% of whom are from racial/ethnic minority families. The four classrooms had a total of 88 students, who were ten-to-11-years old. Among them, 76 students agreed

Fig. 4 The timeline of major events in each classroom related to the design elements. This figure does not show students' continual inquiry and ongoing discourse extended through the whole course

to participate in this research by allowing us to analyze their learning data. The four classrooms were taught by two veteran teachers, each teaching science in two classrooms: Mrs. K working with class 1 (21 students in total) and class 3 (23 students) and Mrs. G working with class 2 (22 students) and class 4 (22 students).

Knowledge building design and implementation

As part of their science curriculum, students in the four classes studied two topics—ecosystems (from September to December) and then human body systems (from January to June)—over the whole school year using a Knowledge Building approach supported by the ITM online platform that interoperated with Knowledge Forum. Students worked on ITM throughout each unit to participate in online discourse, using the note editor and scaffolds provided by Knowledge Forum to write discourse entries. As noted earlier, ITM organized their online discourse based on "wondering areas" (inquiry areas) and idea threads and provided additional support for Journey of Thinking reflection and Super Talk. Each student had access to a laptop during the science lessons to conduct their inquiry activities and discussions. This research only focused on the human body unit. Figure 4 shows the timeline of the major events related to the knowledge building design.

Before the start of the human body unit, the teachers met with our research team to co-design the overarching inquiry process in reference to a set of knowledge building principles, such as authentic problems, collective knowledge, idea improvement, and rise-above (Scardamalia, 2002). The co-design included specific planning of initial kick-off activities, the open envisioning of possible unfolding inquiry directions driven by student interests, and identifying learning resources related to the potential inquiry directions. The researchers then demonstrated new features of ITM to support cross-classroom sharing and collaboration and worked with the teachers to co-design the classroom process, with a shared sense that detailed timing and procedures needed to be determined based on students' inquiry progress.

The human body inquiry was kicked off in early January when students in each classroom participated in a set of hands-on activities experiencing various human body functions (e.g., apple tasting, measuring heartbeat after high kicks). This was followed by a whole class "metacognitive meeting" during which students sat in a circle to review their observations and questions (wonderings) and generate plans for the science inquiry. The questions were clustered into a set of overarching "wondering areas" (e.g., How do humans get and use energy from food?) to guide collaborative knowledge building. The teachers then added the wondering areas to ITM to organize the discourse and inquiry of each classroom (see Fig. 1 for class 2). Students engaged in interactive discourse to share ideas, questions, and inquiry findings. As the inquiry unfolded, giving rise to new questions and directions of inquiry, each classroom conducted further metacognitive meetings to formulate new wondering areas, which were added to its ITM home space. For example, class 2 added new wondering areas related to the blood, brain, and bones and muscles.

As the focal design elements tested in this design-based research study, we used the new features of ITM to support student co-authoring of super notes for cross-classroom sharing and cross-classroom discourse (i.e., Super Talk) focusing on challenging issues identified by students. As students made progress in various lines of inquiry in their home classrooms, the teachers introduced them to the Journey of Thinking (JoT) tool in ITM (see Fig. 2) in late January. Students who focused on a shared wondering area about a human body function worked together to review their knowledge progress based on the online discourse and personal notebooks, and then co-authored a reflective super note using the Journey of Thinking function. Specifically, individual students constructed reflective input by typing in the three sections of Journey of Thinking to identify major questions explored, "big ideas" learned, and questions for deeper inquiry. The Journey of Thinking tool then merged the individual input as the draft of a whole super note, which was co-edited by students before being shared with other classrooms. The deeper questions identified for the further inquiry were used to guide students' subsequent knowledge building activities in their classroom. Students from each classroom were given the time to read the super notes generated by their own peers and by other classrooms.

The implementation of cross-classroom discourse Super Talk included student generation and negotiation of high-potential questions, teacher facilitation for shared interest building, and the collective discourse of students in connection with personal expertise and home room discussions. The human body inquiry progressed further in each class with deeper issues identified. At the beginning of May, students in class 1 suggested a challenging question for the whole fifth grade to discuss using ITM's Super Talk function: "How do people grow?" The teachers shared this Super Talk question with the students in the other three classrooms. Students from the four classrooms then participated in the Super Talk discussion over the next month to contribute their questions and knowledge about how people grow as related to the various body systems that they had been studying (see Fig. 2). At the beginning of June, a whole class metacognitive meeting was held in each room to discuss what students had gained from the Super Talk, build connections with their own inquiries,

Table 2 An overview of the data collection from the four classrooms

	Class 1	Class 2	Class 3	Class 4
Teacher	Mrs. K	Mrs. G	Mrs. K	Mrs. G
Science lessons (45 min each) observed	32	31	29	31
Regular notes posted in the online space of the home class	152	235	196	276
Super notes (Journey of Thinking) shared with other classrooms	5 super notes by 13 co-authors	4 super notes by 21 co-authors	3 super notes by 23 co-authors	4 super notes by 22 co-authors
Contributions to the Super Talk	9 notes from 9 students	6 notes from 4 students	4 notes from 4 students	3 notes from 3 students
Students interviewed	5	7	6	4

and work on deeper questions. More detailed process analyses of the Super Talk are presented and analyzed in Results under RQ3 and RQ4 below.

Data sources and analyses

Table 2 provides a summary of the data collected from the four classrooms. The data sources included (a) classroom observations and video recordings of the science lessons in each classroom during the human body study (two lessons in each week for each classroom), (b) student notes posted in their own classroom's online discourse space (859 notes in total), (c) super notes co-authored by students to synthesize inquiry progress in various areas for cross-classroom sharing (18 super notes in total co-authored by 79 students), (d) records of the cross-classroom Super Talk on ITM that had a total of 22 notes, and (e) transcripts of student interviews. At the end of the learning unit, researchers conducted a semi-structured interview with 20 students, each lasting approximately 15 min. The students were asked to reflect on their experience with collaborative knowledge building and their writing of super notes and participation in the Super Talk

To investigate RQ1, we conducted a qualitative analysis of our observation notes and classroom videos to document the evolution of student inquiry in each classroom, focusing on a set of wondering areas formulated by students. To trace students' participation, we further retrieved quantitative data from ITM that recorded the number of notes posted in each wondering area by various student authors. Comparing the topical areas of the online discourse and the intensity of student contributions between the different classrooms allowed us to identify their common interests as well as unique areas of inquiry about the various human body systems.

To address RQ2, researchers conducted a content analysis (Chi,1997) of the super notes generated by students from the four classrooms. Drawing upon the coding schemes developed through our prior studies (e.g., Zhang et al., 2007), each super note was coded based on two four-point scales, including scientific sophistication (1-pre-scientific, 2-hybrid mixing scientific information with intuitive understanding, 3-basically scientific, and 4-scientific) and epistemic complexity (1-unelaborated facts, 2-elaborated facts, 3-unelaborated explanations, and 4-elaborated explanations). Two researchers coded all the super notes and obtained an inter-rater reliability of 93% (percentage of agreement). The same analysis had been conducted for the super notes generated in a prior iteration of this design-based research in which ITM was not used (Zhang et al., 2020). Comparing the quality of students' super notes between the two iterations allowed us to detect potential enhancements enabled by the ITM features for co-writing reflective super notes using the Journey of Thinking tool. Researchers further analyzed the student interviews in which they reflected on their super note writing. The interviews were fully transcribed and analyzed using a grounded theory approach (Corbin & Strauss, 2014) to understand how students understood and approached the writing of super notes. The first author used NVivo 12 (QSR International, 1999) to read/re-read each interview transcript and create initial raw codes, with new codes added in response to new patterns observed. The initial raw codes were compiled and refined for clarity. The researcher then re-coded all the interview data based on the updated codes. The raw codes and examples were then reviewed to develop theme-based categories representing student views of how to formulate super notes (see the themes reported in Results). The themes were further validated and refined through theme-data and theme-theme comparison.

For RQ3 and RQ4 regarding the Super Talk, we examined the records of the cross-classroom Super Talk in connection with students' inquiry work in each home classroom as documented in researchers' observation notes, classroom videos, students' notebooks, and student interviews. As Lemke (2000) suggested, understanding dynamic learning interactions in an ecosocial system requires analysis of its interdependent processes taking place on different timescales. Adopting this suggestion, our analysis integrated multiple levels and units of analysis, with each unit interpreted in the context of the larger unit and elaborated using the more specific episodes involved. Specifically, our analysis traced student idea development within individual and small-group inquiry in each home class in connection with the major knowledge advances achieved in the cross-community Super Talk. The researchers applied content analysis to examine the epistemic complexity (from 1-unelaborated facts to 4-elaborated explanations) of each note posted in the Super Talk and identified the core conceptual ideas developed to explain how people grow. Based on the conceptual elements and their contributors, we further conducted a temporal analysis to trace backward and identify the related inquiry work in the contributors' home classrooms, as recorded in video recordings, field notes, and online discourse posts. Classroom videos and online posts were further analyzed to identify when and how the ideas were generated and by whom. Student notebooks and interviews were further used as supplemental data sources to triangulate our analysis of the temporal processes and elaborate on how students developed their contributions in connection with their peers.

Results

RQ1: How did students in each classroom develop collaborative inquiry to address core scientific issues of their interests?

In this section, we present our qualitative and quantitative analysis of RQ1, which is meant to develop a general sense of the knowledge building work in each of the four classrooms and to provide the context for investigating cross-classroom interaction. As a brief narrative account, the human body inquiry started in early January and continued until mid-June. Students in each room first participated in a set of kick-off activities that triggered their interest and curiosity about the human body. Students wrote personal questions on Post-it notes. They then attended a whole-class metacognitive meeting to share their questions and cluster them in order to form shared wondering areas. The teacher recorded the wondering areas on chart paper, each with a theme and an overarching question. Students' personal questions were posted next to the most relevant areas. Students with shared interests formed into small, flexible groups, which were adapted over time based on emergent needs. The wondering areas were used to organize students' collaborative work and discourse on ITM (see Fig. 1 as an example), with a discussion space (idea thread) set up for each wondering area. Students then worked individually and collaboratively to conduct inquiry activities within the various areas. New ideas, information, and questions were shared in ITM for continual online discourse. New wondering areas were added based on emergent inquiry questions and directions, such as those regarding senses and immune systems in class 1.

To understand the whole profile of the knowledge building work and discourse of each classroom, we quantitively analyzed student participation in the online discourse of their own classroom, focusing on the various wondering areas. Figure 5 shows the wondering

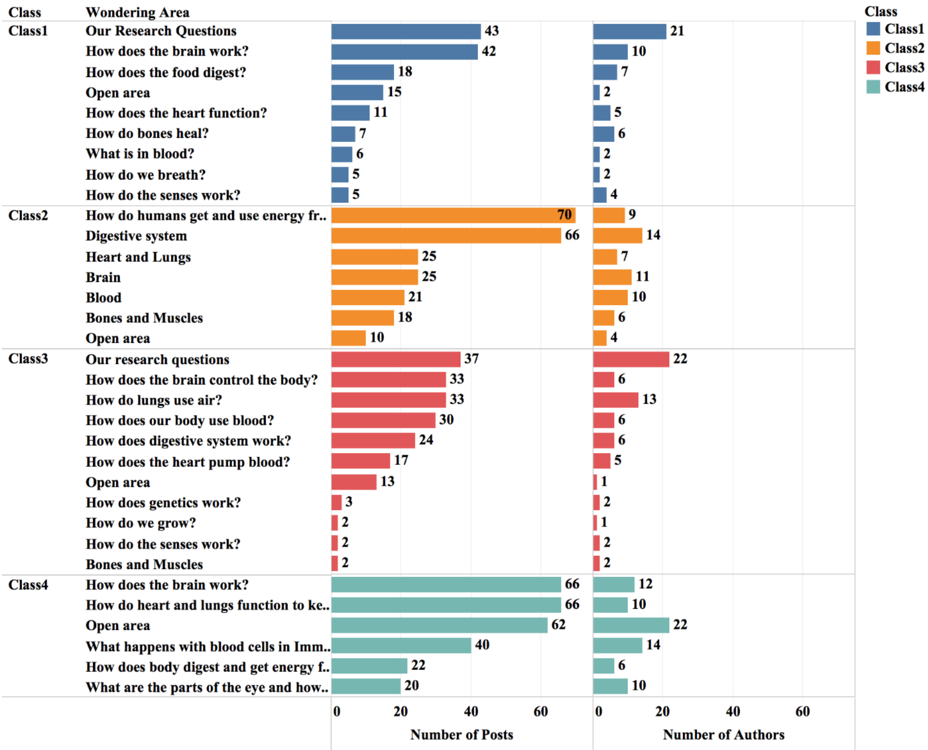

Fig. 5 Student online discourse in each home classroom focusing on their wondering areas

areas of each classroom, the number of notes posted in each area, and the student authors involved.

As Fig. 5 indicates, the four classrooms investigated a common set of inquiry topics related to the major body systems, including the digestive system, brain, heart, and lungs. These common wondering areas were generated early on in each room, partly because the similar kick-off activities involved student experience using such body systems. Each classroom developed its own profile of participation that combined extensive discourse on some of the core body systems and specialized discourse on unique issues identified by its members. In class 1, students had extensive discussions on how the brain works and investigated special issues related to how bones heal and how the senses work. Class 2 actively investigated the digestive system with a unique interest in how the human body obtains and uses energy, which was a topic carried forward from their ecology inquiry conducted immediately before the human body unit. Class 3 had a diverse range of inquiry areas with a unique interest in genetics and growing. Class 4 had the most intensive discourse in the areas of the brain, heart, and lungs, with a specialized inquiry about the immune system and eyes. While building knowledge in the existing areas, students in each classroom continually posted questions and ideas in the Open Area (or Our Research Questions) to explore broader issues and interests, often at the intersection of different body systems.

RQ2: In what ways did students compose their super notes to capture knowledge progress for cross-classroom sharing?

As students progressed with their inquiry over the next two months, they started to use the Journey of Thinking function of ITM (see Fig. 2) to co-author reflective super notes, each of which summarized the collective progress of inquiry in a wondering area. Students involved in each inquiry area reviewed the questions and ideas posted in their online discourse and personal notebooks and recorded their reflection on the inquiry progress, which included the important questions explored, knowledge advances framed as "We used to think" and "Now we understand," and deeper questions to be investigated. Focusing on the deeper

Table 3 Students' views of the super notes (written with the Journey of Thinking tool)

Themes	Examples
Super notes as summaries of big ideas	*I decided to go with the main things that I learned, the things I spend the most time on, like a few weeks, not the things like I found out like in five minutes.*
Super notes present refined ideas	*I wanted to take my really good really deep thinking, really good information to put into it. So, it's really like the best of the best information that I had.*
Super notes as group reflection on the journey of inquiry	*You join together with your whole group, and put together all of your knowledge and questions, and like deeper research questions in the beginning, into one note, that's like super huge.*
Super notes as shareable objects for other classrooms	*To show that I studied all of this and now I'm putting all my information together to show other people and to teach other people. These are the big things that I'm learning about. Because not just your class could see it. It's (for) everybody.*
Super notes help future classrooms learn	*…People gonna become fifth graders. When they come, it (super note) can help them. They can look at our Journey of Thinking and learn more stuff from me.*

Table 4 Student Reflection on Knowledge Advances Using the Scaffolds of "We used to think" and "Now we understand."

	Current study		Prior iteration without ITM	
	We used to think	Now we understand	We used to think	Now we understand
Scientific Sophistication				
Pre-scientific	33%	0%	38%	0%
Hybrid	50%	0%	48%	0%
Basic	17%	0%	14%	18%
Scientific	0%	100%	0%	82%
Epistemic Complexity				
Unelaborated Facts	83%	0%	95%	9%
Elaborated Facts	0%	17%	0%	32%
Unelaborated Explanations	17%	0%	5%	9%
Elaborated Explanations	0%	83%	0%	50%

inquiry questions identified in their super notes, students carried out further investigation to deepen their understanding over the next month and updated some of the super notes based on the new progress. The analysis of student interviews revealed how they understood the purpose and process of the super note writing (see Table 3). The salient patterns capture the various roles played by the super notes, which ranged from reflecting on and refining their own knowledge progress to creating shareable knowledge for other classrooms, including helping future classrooms to learn from their inquiry works.

A total of 18 group-based super notes were composed by the four classrooms using the Journey of Thinking tool, including four from class 1, four from class 2, six from class 3, and four from class 4. Each super note synthesized student knowledge progress related to an area of inquiry in their classroom. To examine the reflective quality of the super notes composed to capture knowledge progress, researchers coded student ideas summarized under "We used to think" and "Now we understand" based on two four-point scales: scientific sophistication (1. pre-scientific, 2. hybrid, 3. basically scientific, 4. scientific) and epistemic complexity (1. unelaborated fact, 2. elaborated facts, 3. unelaborated explanations, 4. elaborated elaboration) (Zhang et al., 2007). Table 4 reports the ratings of students' super notes in comparison with the same measures applied to the super notes created in the previous iteration of this design-based research when ITM was not used.

As Table 4 shows, student ideas recorded under the scaffold of "We used to think," which captured their initial thoughts about the inquiry topics, were mostly pre-scientific or hybrid (mixing scientific with naive understanding) and presented unelaborated information. Their ideas recorded under "Now we understand," which captured the new/deeper knowledge built through their inquiry, were all coded as scientific, mostly presenting elaborated explanations (83%) of how the various human body functions work. For example, in a super note reviewing their inquiry focused on how people breathe, students identified their initial, pre-scientific thoughts: *"[We used to think:] that the lungs were just hollow."* Their updated ideas demonstrated scientific explanations of how the lungs function: *[We now understand:] that the lungs are squishy like a sponge. The lungs are just like a tree. Think of it like this. The stump is like the trachea/throat, the branches are the lungs, the sticks are the bronchi tubes, and the blood cells are leaves; The lungs bring oxygen into the blood, then it's oxygenated blood."*

As Table 4 further suggests, the super notes written by the current students were longer than those generated in the prior iteration of this design-based research when ITM was not used (362.30 versus 170.80 words on average). Their more detailed writing conveyed more sophisticated ideas. The ideas summarized by the current students under "Now we understand" exhibited a higher level of scientific sophistication and complexity than those generated by students in the previous iteration of this research.

RQ3: How did students initiate and participate in the cross-classroom Super Talk, with what knowledge advances?

Besides the ongoing sharing of inquiry progress using super notes, the four classrooms engaged in a shared Super Talk discussion on a challenging topic, which was initiated by students. On May 3, a few students in class 1 noticed the ITM feature for Super Talk and asked their teacher about its function. Mrs. K. explained that this function was for all the classrooms to pool their knowledge together to explore big challenging questions. A whole class conversation was organized to propose challenging issues for the four classrooms to collaborate on. Questions were proposed, including: How are all the human body systems connected? Which two systems are most connected? And how do people grow? The last question received extensive peer comments on how this topic was connected with the different inquiry areas. Several students showed a deep interest in understanding how people grow because they had grown considerably during the school year. The whole class decided to vote for a topic that they felt was most challenging and exciting, and suitable for cross-classroom collaboration. The topic of "How do people grow?" was selected. This Super Talk topic was added in ITM and made visible to all four classrooms. Mrs. K communicated with Mrs. G, and then the teachers advertised the Super Talk question in the other three classrooms. Students expressed excitement about the opportunity to collaborate with peers from the other rooms.

Students from the four classrooms participated in the Super Talk over the next month from early May to early June. A total of 22 notes were contributed by 20 students from the four classrooms to explain how people grow as related to the various body systems (see

Table 5 A summary of student contributions in the Super Talk explaining how people grow

Conceptual elements	Student participants	Example ideas
Bones	2 from class 1 2 from class 2 1 from class 4	- Bones grow from cartilage through the process of ossification, which helps temporary bones to permanent bone. - Spine grows as you grow. - Growth plates are where new bone grows.
Muscles	3 from class 1 1 from class 4	- Muscles grow stronger through physical exercise, which cause little rips. - When muscles are repaired, they get bigger and stronger.
Digestive system	1 from class 4	- Red blood cells take nutrients from food and deliver the nutrients to all parts of the body.
ADP (Adenosine Triphosphate)	1 from class 2	- ATP can be used as energy, stored and converted into ADP (Adenosine di-phosphate). - ADP helps form the muscle placement.
Mitosis of cells	1 from class 3	- Mitosis is the process of one cell splitting into two new cells.
Sleep	2 from class 2	- During sleep stage 2, our body is repairing damage tissues and also growing. - During sleep, the human body releases a small amount of growth hormone.
Brain	3 from class 1 1 from class 3	- Pituitary gland in the brain produces and releases hormones into the body.
Pituitary gland	1 from class 2 1 from class 3	- Pituitary glands release hormones for you to grow.
Genetics	1 from class 3	- Genetics and the pituitary gland can determine your height.

Fig. 2). The Super Talk discourse was interactive, with 41% (n=9) of the notes written as build-ons as opposed to single notes. Based on coding of epistemic complexity, 82% (18 out of 22) of the notes offered elaborated accounts of explanations and facts, and only three notes presented brief unelaborated information.

To understand student understandings generated in the Super Talk, we analyzed the content of the online discourse and identified a series of core conceptual elements used to explain how people grow. Table 5 summarizes the conceptual elements and the related contributors from the four classrooms. Each conceptual element explained the process of human growth from a specific angle, ranging from the growth of muscles and bones to digestion, brain control, growth hormones, and so forth.

During the Super Talk discourse, students built on one another's notes to explain how people grow from the various aspects. For instance, Jane from class 1 first posted a note about how muscles grow: "*When your muscles get a bigger change than they are used to, it causes little rips and when they get repaired, the muscle gets bigger*". Frank from class 2, studying the digestive system and energy, found the connection between growth and muscles. He posted a note in the Super Talk about how muscles use energy from ATP (Adenosine Triphosphate) for muscle placement. And then Tim, who was a member of the immune system group in class 4, extended the understanding by saying "*…they rip which lets out a chemical called cytokines which activates your immune system which repairs it bigger than it was earlier which makes your muscles grow*" (Fig. 2). At the same time, a new viewpoint was presented by Kennedy from class 2, who studied brain and sleep, focusing on how sleep affects growth as related to her inquiry of the brain. Her post highlighted that during the Non-Rapid Eye Movement stage (NREM) of sleep, the body is repairing damaged tissues and growing. And new detailed information about bones was expanded and explained by Henry from class 2 who was studying bones; after reading the existing notes he added "*bone grows from cartilage; they fuse and go through a process called ossification*." Later, his classmate, Frank, who studied the same topic, built on this note and added a more detailed description of the process of ossification: "*Over time, a different type of cell called osteoclasts head to the middle of the bone to help in. Inside osteoclasts, there are hydrolytic enzymes and acids. These enzymes and acids will help dissolve the temporary bone (the cartilage) to make room for the permanent bone (marrow).*" Towards the end of the online discussion, Faya from class 3, who was studying the endocrine system, provided her explanation from this perspective, noting that the pituitary gland releases a hormone that controls growth as it plays an essential role in puberty and metabolism. A cross-cutting connection was further built when the idea of mitosis was brought into the conversation. Blake from class 3, who was studying cells, learned that humans and all their organs are made of cells, and the fundamental way cells grow is from mitosis, and cell growth is how humans grow. He imported his own note about mitosis from the cell discussion that he created in March into the Super Talk; this note was read by another student, Nevan from class 1. Nevan shared this concept of mitosis at a whole-class metacognitive meeting in class 1, leading to an interactive conversation.

RQ4: How did the Super Talk discourse build on and further shape the knowledge work in each home classroom?

Using the conceptual topics and contributors in the Super Talk as tracers, we traced backward to identify the related inquiry work that had been conducted by the students in their home classrooms as the foundation of their Super Talk contributions. Figure 6 depicts the

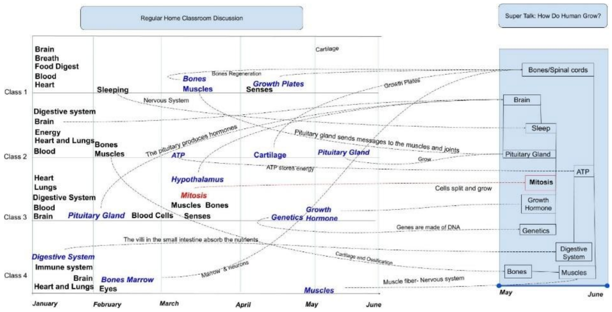

Fig. 6 Tracing idea development in the Super Talk (right box, from May to June) in connection with the related knowledge building work and discourse in each home class based on the first time the main concept appeared in each classroom on a timeline (left box, from January to June)

conceptual elements progressively incorporated in the Super Talk (on the right) and their connections with student inquiry work in their home classroom (on the left). Each dotted line in Fig. 6 illustrates how student contributions to the Super Talk were grounded in the inquiry and discourse in their home classroom.

As Fig. 6 shows, the key ideas developed in the Super Talk built upon student inquiries conducted in their own classroom in the related areas. Students revisited the inquiry works that had been done on the related topics from January to April as they put their knowledge together to explain how people grow. For a deeper analysis, we use two conceptual elements—muscle and bone growth (as related to mitosis)—as examples to elaborate how student contributions to the Super Talk emerged from the inquiry work in each home classroom and develop new connected understandings. Below we provide a chronological account of students' inquiry work in each classroom that gave rise to their contributions to understanding how bones and muscles grow, attending to how students participated as individuals, small-groups, and communities.

Classroom 1

Eight students from class 1 participated in the Super Talk discussion from the perspective of bones, muscles, growth hormones, and sleeping; of those, six students mentioned how growth relates to muscles and bones. The topic of muscles originally branched out from the topic of the heart. At the beginning of January, a group of learners interested in the heart (Hugo, Jane, Maxwell, Nevan, and Otis) first investigated how the heart functions and problems caused by holes in heart tissue. As they accumulated enough knowledge, on March 5, the heart group held a meeting with the whole class, during which they shared their understandings of how blood travels through the circulatory system and made a new connection between heart and bones (that ribs protect your heart). On March 15, the teacher talked to this group to see whether they had new or deeper questions for inquiry. Jane, who had focused on the skeleton, was inspired by the connection between the heart and bones and proposed new inquiry questions: "How do your bones heal?" and "How can bones make blood?". The teacher created an idea thread in ITM for students' inquiry of the new research questions. Later, Maxwell, Nevan, and Otis, who were core members of the heart group, joined Jane to explore these issues. Their thinking about bones and muscles was deepened and elaborated over time to encompass understanding of the various categories of bones (axial bones and appendicular bones), joints, bone fracture, and the treatment of snapped bones (put in a cast). Conceptual connections were built among the different body systems, such as by understanding how the bone marrow creates red blood cells and brain control of joint movement through the sending of nerve signals.

In the above context, in early May, students in classroom 1 initiated the Super Talk topic of how people grow. The students working on bones and muscles were excited to share their knowledge in the Super Talk because it was closely related to their research topics. On May 9, Nevan and Otis co-authored a note in the Super Talk to explain how the brain connects to the bones: "*Humans grow by the brain: the pituitary gland controls the growth hormones and sends messages to the muscles and the joints. The brain helps the body grow. The pituitary gland controls growth.*" Following this note, Jane added the idea of "bones do not grow, but form." This idea triggered interest from two students in class 2 and extended the discussion with the concept of bone ossification later in the Super Talk.

As the above analysis suggests, the students in class 1, who had worked as a group to investigate the heart and bones in connection with the brain, used their existing knowledge to understand how bones form and the role of the pituitary gland. Their ideas shared in the Super Talk became the resource for further conceptual advancement by students from the peer classrooms.

Classroom 2

Classroom 2 contributed to the Super Talk discussion about how bones and muscles grow through building connections with digestion and cells. Tracing back to student inquiry developed within classroom 2, we observed that the classroom members first investigated issues related to the digestive system, brain, heart and lungs, energy, and blood in the first two months. As a theme connecting these topics, students looked at how humans obtain and use energy from food. Focusing on this problem, students developed elaborated understandings of the process of digestion: the digestive system breaks down food and further delivers nutrients through the bloodstream. Based on students' interests in the emerging inquiry, on February 8, the teacher added a new wondering area named "Bones and Muscles." Six members volunteered to investigate this topic. They added key information about layers of bones and cartilage. On March 4, a new connection was made between the digestive system and muscles by Frank, who posted in ITM: "*…ATP is what 'charges' your body… when you eat, ATP is made which then powers up your body… if your body is low on ATP, it will be stored in your muscle cells… ATP is your body's main energy source.*" On April 15, Taylor contributed a detailed explanation of how bones, cartilage, muscles and spine work together to help people stand upright.

After classroom 1 initiated the Super Talk topic of how people grow, on May 11, Mrs. G held a whole class meeting in classroom 2 to advertise the Super Talk topic. Students first read the notes already posted by the other classrooms, discussed how class 2 can learn from the cross-classroom discussion, and further added to it. They commented that although the existing notes talked about the growth of muscles and bones, the information posted so far had not answered the question of *how* exactly bones and muscles grow. The teacher acknowledged the importance of explaining *how* people grow and encouraged students to post non-redundant information to help build collective understanding. After this meeting, a few students worked on explanations of how bones grow, drawing upon the above-noted inquiries about bones, muscles, digestion, and cells. Henry, who first worked with a few peers on how humans obtain energy and later joined in the group inquiring about bones and muscles, built on an existing note about bones in the Super Talk. He wrote: "*Babies are born with 100 more bones than adults, the bones fuse together to make longer bones as we grow. What babies have are not really bones, it is cartilage. With the help of calcium, the cartilage gets turned into bones through the process of Ossification.*" His classmate, Frank, read this note and further built on it by saying: "*I might have a little more info to help you. Over time, a different type of cell called osteoclasts head to the middle of the bone to help. Now, inside osteoclasts, there are hydrolytic enzymes and acids. These enzymes and acids will help dissolve the temporal bone (the cartilage) to make room for the permanent bone (marrow). Also, Ossification will take around 20 years. Once this process is over, the bones will not grow anymore, but will still be able to heal themselves in case you get any unexpected fractures."* Taylor, as a member who studied cartilage, further added that growth plates are connected to the growth hormone to make people grow.

Thus, the participation of classroom 2 included learning from the ideas posted by the other classrooms, reflecting on the knowledge gap regarding *how* bones and muscles grow, and bridging the gap by generating detailed explanations. Their explanations, which built on the prior work conducted by the Bones and Muscles group, contributed deep understandings beyond what had already been posted in the Super Talk.

Classroom 3

In class 3, the topic of muscles and bones emerged relatively late in mid-March involving only two students. The two students did not post any notes in the Super Talk discussion. Instead, students who investigated cells in class 3 made important and unique contributions to the Super Talk, highlighting the role and process of cell mitosis. Below, we trace how their ideas about mitosis developed within their group and classroom and contributed to the cross-classroom discussion.

In classroom 3, one of the most productive lines of inquiry investigated the function and structure of the brain. As a specific insight, students found that the pituitary gland in the brain releases hormones. This topic was further connected to the inquiry about lungs. Students from the lungs group found that the brain and lungs work closely together, noting that oxygen gets to the tissues (including those in the brain) through red blood cells (week 5), and tissues in the body need oxygen (week 6). Blake, a key member of the heart and lungs group, contributed his knowledge about cells during a metacognitive meeting: "*The cells contain sugar except they need the oxygen to turn it into energy*." In week 7, the concept of the cell was expanded to consider white blood cells, such as through Blake's build-on: "*Neutrophils look for things that shouldn't be in your body, and macrophages look for and digest dead germs…Amino acids are what make proteins.*" In a whole class discussion, the teacher asked: "*What tissue of our body needs oxygen?*" Students said: "*Everywhere, because we need our oxygen to survive*." The understanding of tissues and cells was further deepened on March 15 when Blake introduced a key concept related to human growth: "*Mitosis is the process of one cell splitting into two new cells as it is a complex process with many steps*." In the same week, Blake suggested that the teacher create a new thread of discussion in ITM focusing on "how do we grow?" This thread was set up in class 3's own discussion space; however, it received little attention from Blake's peers within class 3.

In May, class 1 initiated the Super Talk topic asking the same question about how people grow. Blake was thus able to connect with other peers from the whole of Grade 5 who were interested in exploring this problem. He joined in the collaboration, with his early note about mitosis copied to the Super Talk space. This idea caught the attention of Nevan, the aforementioned student from class 1. After reading Blake's note, Nevan brought the knowledge about mitosis to a home room discussion in class 1 and extended his peers' understanding (see detailed analysis below).

As such, classroom 3 had done early work related to how people grow within a small group of students; the Super Talk on how people grow provided the opportunity for the students to gain visibility in their home room and connect with broader peers from the other classrooms. Their contributions related to cells and mitosis were enabled by their early inquiry work, serving to deepen the collective discourse and further benefit the partner classrooms.

Classroom 4

Within classroom 4, the topic of muscles and bones emerged from their inquiry about the immune system. Tim and two other class members first investigated the immune system with a guiding question: "What happens with blood cells in the immune system?" This was first explained by Tim in the first month, who wrote: "*Your immune system is a process of white blood cells that kill bacteria, the white blood cells in the immune system are Leukocytes*." This idea was further connected with the inquiry about bones. Tim posted in the fourth week: "*Bone marrow, a tissue inside of your bones, makes white blood cells which enter a system called the lymphatic system, which helps your body from getting diseases… There are 2 different types of blood cells, they are phagocytes and lymphocytes."* From the second month of the human body unit, the inquiry of the immune system was expanded to include HIV and the lymphoid. On May 3, during a metacognitive meeting, the teacher emphasized that May is the "Month of Connection" to understand connections between the different body systems. Tim pointed out a connection by saying: "*Muscles are a huge part of your body. Without muscles, you couldn't blink, jump, smile or have your heartbeat. There are 3 types of muscles: skeletal, cardiac and smooth muscles.*"

After the teacher introduced the Super Talk topic to classroom 4, Tim first read the notes already posted there, making connections with his understanding about the immune system and muscles. He then contributed to the Super Talk by adding a detailed explanation about how muscles grow: "*Muscles grow by when you stress muscle fibers, by lifting heavy weights or doing motions that you're not used to. They rip which lets out a chemical called cytokines, which activates your immune system and repairs it bigger than it was earlier, thereby making your muscles grow. Hypertrophy is how your muscles say you need to work more to make your muscles grow. If you stop exercising, your muscles will go through a process called muscular atrophy which makes your muscles shrink.*" This detailed explanation advanced the understanding of the overarching question one step further.

In a sense, the participation of classroom 4 shared similar patterns with that of classroom 2, involving learning from the ideas from the other classrooms and contributing deeper explanations beyond what had already been posted. At the same time, the contribution of classroom 4 was unique because of its grounding in students' work on the immune system within a small group. Their contribution led to further thinking about cells in the collective Super Talk.

The above analysis of the four classrooms revealed students' extensive efforts to revisit and build on their work on various human body systems as they engaged in a higher-level collective inquiry about how people grow. The data analysis suggests a few patterns of idea traversing from each community to the Super Talk space. In some cases, students directly imported their relevant knowledge from their home room discourse to the Super Talk (e.g., Blake's note about mitosis from class 3). As a more common pattern of contribution, students built on their own work on the various body systems to develop a deeper knowledge of the mechanisms of human growth, contributing to the Super Talk. For example, Nevan and Otis in class 1 built on their inquiry of how bones heal to contribute to the understanding of how muscles and joints grow. Given the complexity of the problem, students often needed to integrate knowledge and expertise across multiple inquiry areas to understand how people grow. For instance, students in class 2 connected their knowledge about digestion and bones to explain the process of ossification.

The analysis further traced how the Super Talk contributed to enriching the subsequent discourse and understandings developed in each home classroom. In early June, toward the end of the Super Talk, each classroom held a face-to-face meeting to reflect on their understanding of how people grow in relation to their own inquiries. We analyzed the discussions to see how the Super Talk contributed to shaping students' understandings and inquiries in their home room. The analysis showed that students brought what they had learned from the Super Talk back to their home class discussion and made further connections with their own inquiries of the various body systems. As an example, the following shows an excerpt of the discussion of class 1.

[135] Teacher/Mrs. K: Your brain cells are dying? Or not making new ones?
[136] Student K8: You are not making new ones, but...they do die as you get older.
...
[138] Student Nevan: I saw something on ITM about chromosomes, it is kind of related to growth.
[139] Mrs. K: What is it? Can you reiterate it? What are chromosomes related to?
[140] Student K7: Mitosis?
[141] Student K5: DNA?
[142] Mrs. K: Oh, Mitosis?
...
[146] Student Nevan: Mitosis is the process of one cell splitting into two new cells. It is a complex process of many steps. One prophase. In prophase the structures called centrioles move to opposite ends of the cell and fibers come out of them and enclose the cell. And in metaphase chromosomes line up in the center of the cell. Each attach to two fibers. Chromosome halves pull apart the cell and divide the membrane. Step three is anaphase and step 4, telophase.
[147] Mrs. K: He is talking about really deep science that's behind this (pointing to the drawing) where the one cell is splitting into two equal parts. So, when you cut an apple...in the center of the apple, [you] get really cut in half. It really does. That's not the same as what is going on here. With mitosis, it gets cut in half, but each half gets exactly the same, the central part… They split apart to make two identical, and it still has that center of the apple. What's in the center in the apple, or the center of the cell?
[148] Student K1: The DNA

[149] Student K2: Chromosomes
[150] Mrs. K: DNA and chromosomes, and what can you tell us about heredity or DNA?
[151] Student K1: Hair color, eye color.
[152] Student K17: Your genes there are like the blueprint.

In the above discussion, students first talked about how the brain relates to growth. In line 138, Nevan made a connection to what he had learned from the Super Talk related to chromosomes. Within class 1, Nevan was one of the key members in the muscles group and later joined the brain group, so he had the basic understanding of neurons and cells needed for understanding the advanced concept of mitosis. With the teacher's support, he was able to share this important knowledge within his home class. In line 146, he elaborated the concept of cell mitosis as related to the class's discussion about how people grow. Since this concept was new and complex, in line 147, the teacher built on Nevan's comments to offer an analogy. In lines 148–152, more students joined in the conversation to connect mitosis with DNA and chromosomes.

During the interviews, students commented on the benefits of the Super Talk that allowed them to exchange knowledge and make connections at a larger scale. As a student mentioned, "*say you don't know something, the chances are, there is somebody else out there that can help you and teach you… I think we could expand a little bit more than just staying with your little group*." Students commented that the Super Talk helped them to learn from other communities while also contributing their own knowledge. As a student said, "*I did not know about all these things at the bottom that were most important to growing. Like fibers, chromosomes, proteins. So that's really important.*" Another student said: "*I saw what other people did… I can put in my own ways to help other people using this information*." By sharing and building on one another's ideas in the Super Talk, their knowledge became part of the larger conversation extended across classrooms. In the interviews, the students who did not post in the Super Talk mentioned they had participated in other ways such as by joining in the related face-to-face conversations or interacting with peers from the other rooms during recess or lunchtime about shared inquiry topics.

Discussion

This research investigated collaborative knowledge building across four classroom communities with the support of ITM. While the existing CSCL research has focused on collaborative learning in small groups or individual classrooms, this study contributes design knowledge and empirical findings that are needed to support collaborative learning on higher social levels (Chen et al., 2021; Cress et al., 2016; Stahl, 2013). In light of the findings, we discuss the following features of the multi-layer interaction design for knowledge building across communities.

Sustained inquiry and discourse in each classroom give rise to diverse ideas and expertise that lead to cross-classroom collaboration

Working with the multi-layer interaction framework, students in each classroom carried out a sustained inquiry and knowledge building discourse to investigate an evolving set of problems identified by their community. Small groups were formed to carry out collaborative inquiry in the various problem area, with ongoing knowledge exchanges in the home class discourse space. As Fig. 4 shows, the four classrooms addressed a range of common problems related to the core human body systems. At the same time, each classroom developed a unique profile of inquiry featuring a few strong inquiry areas with extensive contributions combined with unique topics explored. While the four classrooms worked on the same curriculum unit, students in each class developed unique pathways and profiles of inquiry driven by their diverse interests, progressive questions, and emergent interactions. As our previous studies (Yuan & Zhang, 2019; Zhang et al., 2020) suggested, such common knowledge and diverse expertise developed in the individual classrooms are important for developing productive cross-classroom sharing and collaboration. Students have the common ground to understand and relate to one another's inquiry work across classrooms, learn from the unique inquiry practices and perspectives of their peers, and develop complementary connections for collaborative knowledge building.

Reflective super notes serve as boundary objects for cross-community sharing

On the basis of their knowledge building work in each classroom, students generated super notes to synthesize their inquiry progress for cross-community sharing. Using the Journey of Thinking tool in ITM, students reflected on their inquiry problems, "big ideas" learned, and deeper issues for further inquiry in each area. As the content analysis of the super notes (Table 4) shows, the fifth graders were able to generate high quality reflection on their conceptual advances, evolving from initial pre-scientific understanding toward elaborated scientific accounts. ITM provided support for student writing and sharing of super notes by positioning the Journey of Thinking panel as a reflective layer above student online discourse. Students could individually type reflective entries and then create a merged and refined version. The super notes were automatically shared in the cross-classroom meta-space where students could search and read one another's super notes. With such support, students in the current study developed more elaborate reflection in their super notes than what we had observed in the previous studies where ITM was not used.

The analyses of our current and prior studies revealed the characteristics of super notes to support both epistemic advancement and social boundary crossing (Yuan & Zhang, 2019; Zhang et al., 2020). To differentiate from regular boundary objects, we frame such artifacts as "epistemic boundary objects," which serve to synthesize and consolidate emergent knowledge advances in a community and further support cross-community sharing. As the data analysis (e.g., Table 3) suggests, creating super notes requires students to engage in high-level epistemic processes to reflect on their collective journey of inquiry and synthesize the "big ideas," refined understanding, and deeper issues to further investigate. At the same time, the common structure of super notes makes them able to serve as boundary objects (Star & Griesemer, 1989), enabling knowledge flow between parallel classrooms and different cohort groups across school years. Our previous studies (Yuan & Zhang, 2019;

Zhang et al., 2020) reported detailed social network analyses of the extensive social ties developed among students through the mutual reading of super notes, enabling knowledge flow between different classrooms. The knowledge interaction was further expanded over different school years. Students could gain insight from the super notes of the previous student cohorts (studying the same curriculum area) and further share their knowledge and wonderings with future students. The design strategies and findings of this study enrich the literature on how to use boundary objects to support cross-community interaction (e.g., Huang et al., 2018).

Super Talk enables expansive cycles of knowledge building that re-orchestrate diverse ideas and expertise from the different communities

As a core element in this design-based research, we investigated cross-community Super Talk by which students from the four classrooms worked together to address a challenging problem, drawing upon the knowledge built in their own community. The Super Talk problem—How do people grow? —was not a predetermined task or routine topic expected for the Grade 5 science curriculum. Rather, this authentic problem emerged from students' deepening inquiry of the various body systems and their personal experience as they were beginning a growth spurt. While the students in each classroom conducted a deep inquiry about various human body systems and shared progress through writing super notes, the Super Talk in the last month created an expansive context for higher-level knowledge building, involving a new expansive cycle of inquiry (Engeström, 2014) to develop integrated understandings. Students connected and re-orchestrated their knowledge and ideas about the various body parts to understand human growth as a whole system level phenomenon. With their teachers' facilitation, students read and learned from their peers' notes in the Super Talk, identified gaps and missing links, and further contributed their knowledge and perspectives based on their specialized inquiry of the various body systems. Students' multiple views and diverse inquiries (e.g., bone, brain, digestion, heart, genetics) came into contact in the collective discourse, leading to sophisticated and multifaceted understandings of how people grow (Table 5).

Essential to the multi-level interaction, this study provided a detailed account of the bottom-up emergence and feeding of ideas from each classroom to the collective Super Talk. As students collaborated with peers from different classrooms, they continually revisited their work conducted in the earlier months as individuals and groups and built on their knowledge to develop deep understandings of how people grow. With the input from each classroom, students further pursued interactive discourse in the cross-classroom Super Talk to learn from one another's contributions, search for missing links, add new information, and connect the different pieces of the puzzle to understand how people grow. The results reported for RQ3 and RQ4 provided detailed examples of such cross-classroom interaction and build-on.

The analysis further elaborated on how the Super Talk contributed to enriching and reshaping the discourse and understanding of each classroom. Students brought back some of the key concepts learned from the Super Talk to their home room discussions and further built connections with their ongoing inquiry of the various body systems (e.g., incorporating the concept of mitosis posted by class 3 to class 1). The knowledge gained from the Super Talk helped students to enrich their understanding of the various body systems and engage in deeper sense-making of cross-system connections. The students who participated in the Super Talk played the role of boundary brokers (Star & Griesemer, 1989) to bring new concepts back to home class discussion to address knowledge gaps in their community and stimulate extended discourse. The dynamic interaction served to leverage the visibility and mobility of high-potential ideas favoring collaborative knowledge building. Some of the productive ideas and questions that received little attention in the original community (e.g., Blake's idea about mitosis posted in class 3) captured the broad interests of students from other classrooms in the collective discourse. These findings demonstrate the transformative learning opportunities that can be enabled by extending CSCL to a larger context that involves multiple social levels (Cress et al., 2016; Chen et al., 2021; Stahl, 2013).

Conclusions and implications

Cross-classroom collaboration represents a powerful, expansive learning context that has rarely been investigated. This research contributes new conceptual and empirical insights into how students collaborate across classrooms to build knowledge with technology support. The existing studies on cross-classroom collaboration for knowledge building in school-based settings tested direct sharing of local discussion spaces between classrooms (Laferriere et al., 2012; Lai & Law, 2006). This study contributes to elaborating a more sophisticated, multi-layer interaction approach to cross-community knowledge building, supported by the design of ITM that leverages multi-level idea interaction and discourse. While students in each classroom collaborate in their local (home) discourse space to investigate various problems, they generate reflective super notes to share knowledge progress and challenges in a cross-community meta-space. The super notes serve as epistemic boundary objects to consolidate emergent knowledge advances in each community and further support cross-community sharing. With a mutual understanding of the knowledge work in the different classrooms, students further engage in cross-community Super Talk to investigate challenging problems of common interest, leading to productive idea encounters and sophisticated understandings.

The existing literature on collaborative learning in K-12 settings has mostly focused on small groups and individual classrooms. This research offers much needed design strategies and empirical accounts of cross-community interaction, which builds on and further expands students' collaborative discourse in each classroom community. As the results suggest, cross-community collaboration creates an expansive and dynamic context for high-level inquiry and continual knowledge building. Students have the chance to meet with an expanded pool of ideas, problems, and people beyond the boundaries of different groups and classrooms, develop mutual and complementary knowledge connections, and re-orchestrate the diverse ideas and expertise developed in different classrooms to pursue joint inquiry and collective discourse focusing on complex challenges and interconnected problems. The cross-community discourse builds on the inquiry work of each classroom to develop expanded cycles of inquiry and further feeds back to enriching student inquiry and dialogue within each community.

The results of this research further elaborated a set of principles and strategies that may be used to harness the power of collaborative learning across social levels on a larger social scale. Enriching the existing strategies to deal with the challenge of information overload in online discourse shared by a large number of participants Li et al., 2014; Wen et al., 2017; Wise, Cui, & Vytasek, 2016), this research showcases a multi-layer interaction design that integrates the local discourse spaces of co-located communities with a cross-community meta-space for larger collective discourse. In their local discourse spaces, members of different classrooms pursue personal and collaborative inquiry based on students' evolving interests, curriculum expectations and resources, and time schedule, with their online discourse dynamically evolving in the context of face-to-face classroom activities. The meta-space shared between different classroom communities further enables broader sharing and collaboration focusing on high-level problems and conceptual advances. Based on this research, we offer a few suggestions on the meta-space design. Firstly, the meta-space should be designed as a space for developing and sharing high-level knowledge artifacts that can further serve as boundary objects to support cross-community understanding and inquiry. Super notes provide an example of such artifacts for synthesizing progressive scientific inquiry; other forms of epistemic boundary objects may be designed to support cross-community collaboration in different settings. Secondly, the design of the meta-space needs to support dynamic information flow with local discourse spaces through social or technology-based channels. Cross-community collaboration (such as Super Talk) may be incorporated to support extensive efforts of collaborative problem solving that require the integration and orchestration of diverse perspectives and expertise. Finally, knowledge shared and developed in the meta-space represents a collective knowledge resource (asset) that can be continually accumulated, re-used, and expanded across learning contexts and time frames. This resource—which may involve multimodal discourse and representations—needs to be represented, indexed, and linked in an effective manner that eases continual re-use by students across different learning units and school years, leveraging their personal and collective capacity of knowledge building.

This research has several limitations. Firstly, this study was focused on examining the new supports for super note writing and cross-classroom Super Talk, so it did not conduct detailed analyses of students' online discourse and temporal inquiry processes in each classroom. Readers interested in such detailed analysis may refer to other papers based on this design-based research project (Zhang et al., 2018, in press). Secondly, this research only tested cross-community knowledge building based on a set of four classrooms. The Super Talk about how people grow only involved a small sample of students due to the short time available near the end of the school year. As productive cross-community collaboration takes time and depends on the development of local knowledge practices and expertise in each community, future design and research should create opportunities and infrastructures to implement cross-community knowledge building over longer terms and situate such collaboration in systematic efforts of classroom reform and school change. The multi-layer interaction design may be expanded to support cross-boundary collaboration among heterogeneous communities (e.g., students and researchers with different expertise) that work on interdisciplinary problem solving and knowledge building. The multi-level interaction framework may facilitate interdisciplinary interaction through co-design and use of the boundary objects in a meta-space.

Building on the current study, our researcher-teacher team has implemented another iteration of this design-based research to support cross-community knowledge building over a longer time in a new science area (e.g., ecosystems). Our analysis will take a deeper dive into the teachers' new roles and collaborative practices to support cross-classroom collaboration. We are also planning further efforts to test our design framework on a larger scale in an international network of classrooms. Students from different sites collaborate across boundaries to investigate critical challenges facing the local and global communities, supported by ITM and other technology infrastructures.

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Availability of data and material Following our IRB protocol, the data of this study cannot be made openly available. Those who are interested to access the detailed coding frameworks and data samples can send their requests to the authors.

Code availability The Idea Thread Mapper (ITM) software is freely available to educators and students for classroom use. Developers who are interested to create or integrate software tools inter-operatable with ITM are welcome to reach out to the authors about their needs.

Declarations

Conflicts of interest/Competing interests The authors have no conflicts of interest in the work reported in this study.

Ethics approval This study was conducted in compliance with the research protocol approved by the University at Albany IRB (IRB #14-E-140).

Consent to participate Following the IRB protocol, this study obtained signed consent forms from all the research participants, including each student participant (through child assent and parent/guardian consent) and teacher.

Consent for publication We, Guangji Yuan, Jianwei Zhagn, Mei-Hwa Chen, give our consent for the publication of identifiable details, which can include photograph(s) and/or videos and/or case history and/or details within the text to be published in International Journal of Computer-Supported Collaborative Learning.

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