Intern. J. Comput.-Support. Collab. Learn
https://doi.org/10.1007/s11412-021-09353-7

Agency to transform: how did a grade 5 community co-configure dynamic knowledge building practices in a yearlong science inquiry?

Dan Tao[1] · Jianwei Zhang[2]

Received: 24 March 2021 / Accepted: 22 July 2021

Abstract

This study explores emergent reflective structuration as a new form of shared regulation. The purpose is to support students in taking on high-level epistemic agency as they co-configure dynamic inquiry pathways that unfold over long periods of time. With the teacher's support, students not only regulate their inquiry and collaboration following pre-scripted structures, but they also co-construct shared inquiry pathways to frame and reframe their community practices in response to progress and needs that emerge over time. Our data analysis investigates the temporal and interactional processes by which members of a Grade 5 classroom co-configured their knowledge building pathways in a yearlong science inquiry focusing on the human body systems. As a co-constructed structure, students co-formulated an evolving chart of "big questions" that signified shared inquiry directions with the teacher's support. The inquiry process was supported by Knowledge Form and Idea Thread Mapper, which visualizes the online knowledge building discourse based on temporal streams of inquiry focusing on the "big questions." Qualitative analysis of classroom observation notes, videos, student artifacts, online discourse, and student interviews documented nine "big questions" co-formulated by the community over time. Further analysis revealed students' agentic moves to expand, deepen, and reframe the knowledge building work of their community. Analyses of online discourse and a pre-and post-test showed productive idea contributions, interactions, and knowledge outcomes. Conceptual and practical implications are discussed.

Keywords Epistemic agency · Knowledge building · Opportunistic collaboration · Reflective structuration · Socially shared regulation · Transformative CSCL

At a time when the rapidly changing world enters a new era facing extraordinary challenges, researchers in the field of computer-supported collaborative learning (CSCL) call

✉ Dan Tao
dantao1106@gmail.com

1 Advanced Innovation Center for Future Education, Beijing Normal University, No. 19, Xinjiekouwai St, Haidian District, Beijing 100875, People's Republic of China

2 Department of Educational Theory and Practice, University at Albany, SUNY, Albany, USA

Published online: 20 September 2021

for critical effort to reflect on existing theories and designs in this new context, address potential tensions and blind spots, and work towards educational transformation (Cress et al., in press; Roschelle, 2020; Wise & Schwarz, 2017). In this paper, we argue for the need to investigate and support more dynamic, creative, and transformative forms of collaborative inquiry through which students continually address emergent challenges and move beyond static frameworks and boundaries. In particular, the study reported here investigates how members of a fifth-grade science classroom co-regulated their dynamic knowledge building processes over a school year, leveraging co-constructed inquiry structures that engaged student epistemic agency.

Envision creative, dynamic, and transformative CSCL for a new era

Our society is entering a new era featuring a hyper-connected "white-water world" with constant rapid changes and ever-emerging complex challenges (Pendleton-Jullian & Brown, 2018). This trend has been further intensified by the current worldwide events, including the pandemic, climate change, racial and political tensions, and technological transformation. To prepare students for the new environment, educational reforms need to cultivate adaptive minds and competencies for all students. These reforms must also address traditional gaps and inequalities while leveraging student agency for shaping productive futures beyond established expectations, structures, and boundaries (cf. Bereiter & Scardamalia, 2014; Gutierrez & Barton, 2015; Sawyer, 2015).

To revive CSCL as a pedagogical option for this emerging reality, we argue for the need to envision more creative, dynamic, and transformative forms of collaborative learning and inquiry. Designs for such practices may tap into how creative knowledge work is socially organized within knowledge organizations embedded within a transformed social and technological environment. Major cultural shifts are taking place in real-world knowledge work, changing from fixed to ever-evolving visions and goals; from stable functional teams to flexible collaboration and cross-boundary idea contact; from prescriptive management to opportunistic planning based on emergent changes; and from centralized control to distributed leadership (Engeström, 2008; Gloor, 2006; Hagel et al., 2010; Sawyer, 2007). As such cultural practices pervade various social sectors, it becomes necessary for society members to develop new adaptive competencies and mindsets. Pendleton-Jullian and Brown (2018) use the metaphor of white-water kayaking to describe such habits of mind. Instead of pushing forward along a fixed path, learners, like kayakers, need to constantly read the landscape and reposition their center of gravity in order to participate in and shape the flow of knowledge.

What might dynamic and transformative forms of collaborative inquiry look like among students? We identify a few key features in light of the literature. First, transformative inquiry requires students to take on creative roles to co-construct shared knowledge goals, processes, and spaces (Damsa et al., 2019; Goodyear & Dimitriadis, 2013; Hakkarainen, 2009; Kali et al., 2015; Zhang et al., 2018). Instead of working with pre-scripted learning goals and activities, learners interact with one another and their teacher to co-construct specific arrangements of collaborative processes, which are adjusted based on emerging needs through students' active involvement.

Accordingly, such transformative inquiry requires an "expansive framing" (Engle et al., 2012) of sustained trajectories of inquiry (Tao & Zhang, 2018; Zhang et al., 2009, 2011, 2018). Instead of framing the inquiry process as discrete, pre-packaged tasks and activities, students engage in an ever-deepening inquiry journey that extends and expands across different activity contexts. Their current work builds on what they have done in the past and further informs future inquiries. They generate progressive questions, navigate unfolding flows of ideas, and constantly connect with different problems, ideas, and people for deeper inquiry, moving beyond the existing conceptual frames and social boundaries.

Such transformative inquiry entails dynamic collaboration and improvisational discourse (Sawyer, 2015). Instead of working in fixed small groups set up by the teacher to complete various task components, students participate in "opportunistic collaboration" (Zhang et al., 2009). Small groups are formed, disbanded, and reformed over the whole course of the inquiry based on emergent needs and connections, leading to dynamic idea contact, build-on, and advancement (Siqin et al., 2015; Zhang et al., 2009).

Such transformative inquiry processes are essential to the Knowledge Building pedagogy (Scardamalia & Bereiter, 2014), which uses a principle-based approach to organize student interactions for continual idea improvement (Scardamalia, 2002; Zhang et al., 2011). In each knowledge building initiative that extends over several months, students work with their teacher to identify what they need to understand, plan and improvise various inquiry activities, and reflect on collective and personal progress in light of a set of principles. As progress is made, they identify new and deeper problems, spurring ever-deepening knowledge building actions and discourse.

A core challenge is understanding how the open-ended, ever-evolving process of collaborative inquiry can be organized, regulated, and supported in a manner that leverages students' agency and creative imagination. Existing research has made advances in examining students' self- and socially shared regulation of collaborative learning (Järvelä & Hadwin, 2013; Järvelä et al., 2016). The regulatory processes extend metacognitive monitoring, goal setting, and adaptative control to group-level practices. However, the type of collaborative activities investigated in this research area tends to be relatively short (i.e., a few sessions) and pre-structured. Students are asked to carry out well-defined collaborative tasks in fixed small groups using given resources, tools, and collaboration scripts (Kirschner & Erkens, 2013). Working with scripted activities, students' self- and shared regulation are often limited to understanding the requirements, dividing up the given tasks, and meeting the requirements (Rogat & Linnenbrink-Garcia, 2011); rarely do they have the chance to make transformative changes in inquiry directions and group structures based on emergent interests.

Moving forward, researchers call for investigations that attend to students' strategic adaptation of shared goals and processes in temporally evolving learning situations (Järvelä et al., 2019). As a step toward this direction, the current study explores students' adaptive regulation of knowledge building practices that continually unfold and transform. Students not only regulate their collaborative learning in pre-structured spaces but also reconfigure their collective work as opportunities emerge and pursue new directions beyond the existing frames and boundaries.

Reflective structuration and transformation of dynamic knowledge practices

To address the above needs, we developed a new approach to shared regulation of dynamic knowledge practices: reflective structuration and transformation (Tao & Zhang, 2018; Zhang et al., 2018). Whereas the existing theories of socially shared regulation primarily build on psychological constructs such as metacognitive monitoring, goal setting, and decision making (Järvelä & Hadwin, 2013; Järvelä et al., 2016), reflective structuration adopts a sociocultural and sociological view on the *public* organization of human action. Theories in sociology (Archer, 1982; Giddens, 1984; Sewell, 1992) highlight that social actions and practices are sustained and transformed through the interplay of human agency and social structures. Giddens (1984) uses the term "structuration" to emphasize that social structures, as systems of social action, are in the process of being continuously produced and reproduced. Building on Giddens, Sewell (1992) defines social structures as "sets of mutually sustaining schemas and resources that empower and constrain social action and that tend to be reproduced by that social action." (p. 19) The shared structures, reified using various resources, serve to mediate and regulate participants' ongoing participation, enabling continuity of social practice across people, time, and places. In the same process, the structures are reproduced and transformed, driven by human agency. Goodwin's (2017) research in cultural archaeology further offers a detailed view of the cumulative transformation driven by human agency and creativity. An actor can build new actions by performing "structure-preserving transformations" on resources created by others' actions in a public environment. The actor reuses parts of an earlier pattern of action with modification to build new actions, which generate new patterns and resources in the public space, shaping the temporal unfolding of future actions by other actors.

Building upon the above theories, we define reflective structuration as a reflective, emergent process by which students, with support from their teacher, co-configure shared inquiry structures over time to channel their individual and collaborative efforts for ever-deepening inquiry. As a core assumption, reflective structuration engages students in double-cycle construction: together with the teacher, students build not only content knowledge but also the social contexts and structures in which they work, leading to emergent changes of shared structures that allow their inquiry and collaboration to deepen, expand, and transform over time. This assumption is empirically supported by our previous analysis of a set of design-based research studies conducted in elementary school classrooms with the Knowledge Building approach (Tao & Zhang, 2018; Zhang, 2013; Zhang et al., 2018). Detailed analysis revealed a unique type of inquiry structure that was not predesigned a priori, but rather co-constructed during the ongoing process of collaborative inquiry. The co-constructed structures capture the systematic features of the knowledge practices of a community and provide students with shared interpretative frames for their unfolding actions, including shared knowledge goals, inquiry processes, and social participatory roles, as informed by the guiding principles and values of the knowledge building community (Zhang et al., 2018). Such structures are reified and represented using various resources, such as using co-constructed maps of inquiry directions and processes to guide student participation, interaction, and reflection.

In light of the emergent process of reflective structuration, the design and implementation of long-term knowledge building practices in classrooms require a shift of from a prescriptive to emergent learning design. Prescriptive learning design is akin to the way a designer specifies paths in a park based on a blueprint in order to direct people's movement, in part by setting up signs to discourage walking off-course. In adopting an emergent design approach, the designer creates a relatively open space in which participants are able to explore based on their specific contextual needs. The trails left behind from these participants' engagement reveal what we think of as desire lines, which may then selectively be paved to guide subsequent people's movement. This emergent design approach represents a productive strategy to design complex social systems and spaces (Johnson, 2001; Pendleton-Jullian & Brown, 2018; Sawyer, 2005). The reflective structuration framework leverages this emergent design strategy for designing collective knowledge building practices as a complex, dynamic system. While participating in the initial, exploratory inquiry faciliated by their teacher, students generate “social trails” of inquiry in the form of inquiry questions, interests and participatory roles. Building on the emergent inquiry trails, the students and teacher work together to construct shared inquiry structures to frame what they should inquire about and how, thus shaping the unfolding inquiry pathways. Working with this emergent design requires the teacher to shift her/his focus from instructional *intentions* to close *attention* to what is going on in the classroom, so as to discover emergent inquiry interests and progress, and subsequently to seize on opportunities to catalyze deeper inquiry and collaboration in existing areas or launch new lines of inquiry possibly beyond the teacher’s initial plan.

Our prior studies have elaborated the iterative, emergent processes through which students co-construct shared inquiry structures as their work proceeds (Tao & Zhang, 2018; Zhang et al., 2018), featuring “structure-preserving transformations” (Goodwin, 2017). Students work with the initial structures and conditions in their context to carry out exploratory inquiry and discourse; co-monitor emergent inquiry directions, idea progress, and social connections as the inquiry proceeds; and co-create more elaborated/expanded inquiry structures over time to reshape their inquiry actions and interactions. With the co-constructed structures mediating and reshaping the unfolding flows of inquiry in a collaborative community, the teacher’s traditional roles to structure, monitor, and orchestrate learning processes can be distributed to the community in major ways. Students, with the support from their teacher, enact collective dynamic control to monitor and chart the ever-deepening course of inquiry as it evolves and transforms beyond initially set frames and boundaries.

The double-cycle constructive process to build shared structures for knowledge building occurs within a public space, which is situated in the classroom and further extended through online platforms such as Knowledge Forum (KF) (Scardamalia & Bereiter, 2014) and Idea Thread Mapper (ITM) (Zhang et al., 2018). KF provides a communal knowledge space organized into different views (workspaces). Within each view, students write and build on one another’s notes as they participate in knowledge building discourse, mirroring and extending student conversations that took place face-to-face in the classroom. As a meta-level support to enable students to monitor collective discourse and form/reform shared inquiry directions and connections, our research team (Zhang & Chen, 2019; Zhang et al., 2018) designed Idea Thread Mapper, which interoperates with KF. Core features include (a) visual tools for students to co-organize shared inquiry areas; (b) temporal display of idea threads, each representing a conceptual stream of online discourse to address a shared problem; (c) analytical support for tracing students’ individual contributions and collaborative roles; (d) reflective syntheses (“super notes”) of each thread of inquiry to highlight the progress made and deeper research needed; and (e) a meta-space for cross-community sharing and discourse. We conducted design-based research in a set of Grade 3–6 classrooms to elaborate the processes of reflective structuration with ITM support. With their teacher’s support, students engaged in “metacognitive meetings” (MM) to reflect on emerging interests and ideas, form/reform shared areas of curiosity and inquiry directions, and organize themselves into groups. Such reflective processes enhance student knowledge building, leading to more interactive build-on contributions, cross-topic connections, and deeper understandings (Zhang et al., 2018).

Leverage student agency for transformative knowledge practices

As the above studies suggest, the co-construction and transformation of inquiry structures offer a social and adaptive form of shared regulation for dynamic knowledge practices in which students take on high-level epistemic agency. Unlike prescriptive inquiry structures that often undermine students' agency and freedom, co-constructed inquiry structures may open opportunities for students to continually deepen and adapt their knowledge building practices beyond preset frames and boundaries. The current study intends to offer a more in-depth view of how young students enact epistemic agency as they co-construct shared inquiry structures to shape and reshape their knowledge building practices.

Scardamalia and Bereiter (1991, 2014) introduced the concept of epistemic agency to highlight high-level student responsibility for charting knowledge building goals and processes. Recently, scholars have further elaborated this concept to include its social and cultural dimensions, such as mobilizing resources to achieve their goals, shaping the social systems that they are working in, and transforming the structures and resources as needed (Damsa et al., 2010; Gutierrez & Barton, 2015; Miller et al., 2018; Varelas et al., 2015). Drawing upon the literature, we consider epistemic agency as a personal and collective capacity enacted by students to shape their courses and contexts of joint inquiry for valued outcomes. This capacity includes creating projected (imagined) futures in light of the present and past progress; constructing, evaluating, and modifying courses of personal and collaborative actions; and reconfiguring the social structures and spaces (e.g., visions, norms, relationships, resources) for valued outcomes, which may lead to consequential changes affecting other individuals and the community as a whole. Underlying such moves is a set of cultural and epistemic dispositions, such as a zest for inquiry and problem finding, the tendency to be open-minded and to look beyond what is given, the desire to play with new ideas and tinker with boundaries, the ability to formulate provocative questions and persist in a line of inquiry, and a sense of empowerment to co-design one's own learning trajectories (Gutierrez & Barton, 2015; Perkins et al., 1993).

Research goal and questions

This study was intended to investigate how reflective structuration and transformation may afford opportunities for students to enact epistemic agency for ever-deepening inquiry with the support of their teacher. The context was a Grade 5 science classroom that engaged in a yearlong inquiry on how human body systems work. The inquiry process was organized using a reflective structuration approach guided by the core principles of knowledge building (Scardamalia, 2002). Students worked with their teacher to frame/reframe what they should investigate as progress was made through student interactions within the collaborative discourse. As an iterative, dynamic inquiry structure, their teacher engaged students to co-construct and update a chart of "big questions" to guide their inquiry. The evolving "big questions" were used as a reference framework for both students and the teacher to monitor and navigate the collaborative knowledge space, form flexible groups, and reflect on emergent progress and needs.

In the above context, we investigated three research questions. (a) How did students and their teacher formulate/adapt the chart of "big questions" to co-organize and sustain its inquiry over a school year? (b) How did students' agentic inquiry moves result in emergent and transformative changes, such as shaping, expanding, reframing, and re-organizing of their collective inquiry? And (c) to what extent did such dynamic processes support productive knowledge building, as reflected through analyses of students' collaborative discourse and expressed personal understandings?

Methods

Participants and classroom contexts

This study was conducted in a Grade 5 classroom at a public elementary school in the northeast region of the United States. The participants comprised 22 students in fall and 21 in winter/spring (three students left and two new students joined in the middle of the school year). Students investigated the human body systems over a whole school year with two science lessons each week. Although human body study was a routine topic in the science curriculum, it offered rich opportunities for students to develop personally relevant inquiries (about themselves) and understand the human body as an example of inter-connected complex systems.

The teacher, Mr. S, had 15 years of teaching experience. Before this study, Mr. S and two other Grade 5 teachers from the same school participated in a three-day workshop organized by our research team focused on a principle-based design of knowledge building. Five guiding principles were adopted from the Knowledge Building pedagogy (Scardamalia, 2002; Scardamalia & Bereiter, 2014), including (1) *Idea-centered community*: Each student is a valued member who is willing to share diverse ideas and questions for peer comment and build-on contributions; (2) *Epistemic agency*: Students work as epistemic agents to identify problems, develop ideas, evaluate knowledge progress, and chart the pathway of learning; (3) *Continual idea improvement*: Ideas are continually generated and improved to address deepening questions and challenges; (4) *Collective efforts*: Students make collaborative and complementary contributions to advance the community's understanding; and (5) *Rise-above*: Students work with diverse questions and ideas to generate coherent understandings and higher-level formulations of problems. These principles were used to guide the teacher's emergent design and ongoing reflection during the human body inquiry. Weekly/biweekly teacher-researcher meetings were held to reflect on student knowledge building progress and discuss possible strategies to facilitate more in-depth work.

Classroom implementation

Based on the school's science curriculum arrangement, understanding how human body systems work was identified as the overarching theme for Grade 5 science inquiry in the new school year. The human body inquiry unfolded as an open and dynamic process based on students' emerging problems and interests. Specifically, a teacher-planned kick-off activity was implemented in mid-September. Students watched a short video about the amazing functions of the human body, which triggered deep interest among students. Mr. S facilitated "metacognitive meetings" during which students sat in a circle to engage in reflective dialogue about their inquiry work. Students shared personal questions and interests about the human body, out of which they subsequently co-formulated a set of overarching "big questions" for their community to investigate (see "Results" section). Students with shared interests formed opportunistic groups to investigate each "big question." Their inquiry activities involved student-directed experiments and observations, individual and group reading and note-taking, small group discussion and demonstration, and whole-class knowledge building talks. The knowledge building discourse was extended through the use of KF as a public and collaborative space. Students wrote *notes* to contribute questions, ideas, and information from relevant sources and *built on* one another's notes to engage in interactive discourse.

As the inquiry proceeded, around mid-December and early January, the community conducted metacognitive meetings to review progress in the existing inquiry areas and further identify new problems and challenges. This reflection was supported by ITM, which displayed online discourse based on the existing inquiry areas (i.e., "big questions") to show the temporal progress, interactive build-on within and across areas, and student participation in each area. Students further discussed new questions and interests for further inquiry. A set of new "big questions" formed while some of the existing questions were reframed to highlight the deeper issues about each body system. New flexible small groups were set up based on the restructured inquiry directions.

From February to June, students conducted further collaborative inquiry based on the updated "big questions." In mid-May, students working on each new "big question" reviewed their online discourse using ITM and synthesized what they had learned and what they still needed to know. In late June, students from the five Grade 5 classrooms participated in a cross-classroom event to share their knowledge progress and questions with peers, teachers, and parents.

Data sources and analyses

The data sources included observations and video/audio recordings of classroom activities, classroom artifacts, student interviews, online discourse (a total of 667 KF notes), and pre- and post-test. The first author observed every science lesson and used a classroom observation sheet to record the classroom activities, student ideas, and notable teacher scaffolding. Major collaborative activities such as whole class meetings and small-group sessions were video- or audio-recorded.

To investigate how the community (students and the teacher) worked together to adapt the chart of "big questions" to sustain its collective inquiry over the school year, we conducted a qualitative analysis to trace the formulation of the initial questions, addition of new questions, and reframing of existing questions. The analysis was based on the observation notes and further elaborated using the video/audio recordings. Videos of reflective classroom meetings were transcribed and analyzed using a narrative approach (Derry et al., 2010) to build a detailed storyline of how each "big question" was formulated and adapted. To further trace how students' inquiry and discourse unfolded in light of the evolving inquiry directions, we conducted content analysis (Chi, 1997) of online discourse by coding each KF note based on the "big questions" addressed. Two raters independently coded 20% of the notes, resulting in an inter-rater agreement of 98.5% (*Cohen's Kappa* = .95).

To understand how students' agentic moves led to transformative changes in their knowledge building work, we conducted qualitative analyses of the major structure changes in the human body inquiry. In light of the whole journey of inquiry depicted by analyzing the first research question, we identified critical episodes when changes and adaptions were made to the chart of "big questions." The episodes included (a) the emergence of the initial "big questions" based on student interests in late September, (b) expanding the "big questions" in early October to accommodate new emergent interests, (c) reframing shared inquiry directions in mid-December to early January based on updated knowledge and emergent problems, and (d) formulating "rise-above" conceptual topics at the intersection of the different body systems. For each episode, we analyzed the related classroom observation notes, videos, and artifacts to examine how students' interactive input led to the framing and reframing of shared inquiry directions with the teacher's facilitation. We transcribed and analyzed the video records of whole class metacognitive meetings in which a new framing of inquiry directions was negotiated. Findings from the video analysis were cross-linked with student work recorded in other data sources, including student notebooks, classroom artifacts, student interviews, online discourse, and the threads of ideas organized by students in ITM.

To analyze student knowledge building enabled by the dynamic organization of the inquiry process, we conducted social network analysis (Carolan, 2014) and content analysis (Chi, 1997) of online discourse. The social network analysis examined who built on whose notes in the online discourse in the first and second half of the yearlong inquiry. Drawing upon our previous studies (Tao & Zhang, 2018; Zhang et al., 2007), the content analysis coded student notes based on different types of knowledge contributions, including questioning, explaining, using evidence, referencing sources, and connecting and integrating (see Table 1). Student questions were further coded based on (a) fact-seeking versus explanation-seeking questions, (b) initial wondering versus idea-deepening questions, and (c) single-area versus cross-area questions. For KF notes offering personal explanations, we coded the scientific quality of student ideas on a four-point scale: 1: pre-scientific, 2: hybrid, 3: basically scientific, and 4: scientific.

A pre-and post-test was used to assess students' personal understandings of human body systems. The test included nine open-ended questions, each requiring students to explain a specific issue or phenomenon related to a body system connected with other systems. For example, a question focusing on the skeleton and muscular system in connection with nervous control asks: "One day a little boy, Jack, placed his hand on a hot stove, and he quickly moved his hand away, so he did not get burned. Draw a picture below to show the important body parts that were involved in this process. How did these body parts work together to help Jack avoid a possible burn?" This test was first administered in mid-September and then again in mid-March. Due to changes in the student population and absenteeism, only 13 students took both tests. Using the rubric presented in Table 2, we coded their responses to each question based on levels of scientific quality (1: pre-scientific to 4: scientific) as well as exploratory coherence and connectedness (from 1: describing the body parts involved, to 2: explaining the processes based on a single system, and 3: integrated explanations involving multiple systems working together). Two raters independently coded all answers, resulting in an inter-rater agreement of 99.15% (*Cohen's Kappa* = .98).

Results

How did the community formulate and adapt the chart of "big questions" to co-organize its collective inquiry?

Our analysis traced the initial formation and ongoing adaptation of the "big questions" used to frame shared inquiry directions. Figure 1 summarizes the evolution of the "big questions." As brief highlights, the community first formulated a set of four guiding questions (Q1, Q2, Q3, and Q4) in late September based on students' personal questions

Table 1 Coding schemes for analyzing online discourse

Level 1	Level 2		Description
Questioning	Dimension a	Fact seeking	Questions asking for factual information
		Explanation seeking	Questions in search of explanations
	Dimension b	Initial wondering	Questions searching for general information about a theme-based area
		Idea deepening	Questions searching for deeper and more specific information based on ideas discussed
	Dimension c	Single-area question	Questions focusing on addressing one single "big question"
		Cross-area question	Questions focusing on addressing two or more connected "big questions"
Explaining	Pre-scientific (1)		Misconceptions based on naïve framework of understanding
	Hybrid (2)		Misconceptions that have incorporated scientific information but show mixed misconception/scientific framework
	Basically scientific (3)		Ideas based on scientific framework, but not precisely scientific
	Scientific (4)		Explanations that are consistent with scientific knowledge
Using evidence			A posting that describes experiments, and observations to support or challenge an explanation
Referencing sources			A posting that introduces information from readings/websites and uses the information to deepen ideas and generate questions
Connecting and integrating			A posting that connects different ideas to generate a synthesis, summary, or integrated solution

Table 2 Coding scheme for each open-ended question in the pre-/post-test

Scientific quality of ideas	No answer or not relevant (0)	Student provides no or irrelevant response(s)
	Pre-scientific (1)	Misconceptions based on naïve conceptual framework
	Hybrid (2)	Misconceptions that have incorporated scientific information but show mixed misconception/scientific framework
	Basically scientific (3)	Ideas based on scientific framework, but not precisely scientific
	Scientific (4)	Explanations that are consistent with scientific knowledge
Explanatory coherence and connectedness	No answer or not relevant (0)	Student provides no or irrelevant response(s)
	A focus on body parts (1)	An answer that describes relevant body parts without explaining the process
	Single system explanation (2)	An answer that describes the body parts and process focusing on one particular body system
	Integrated explanation (3)	An answer that describes the body parts and process involving multiple body systems working together

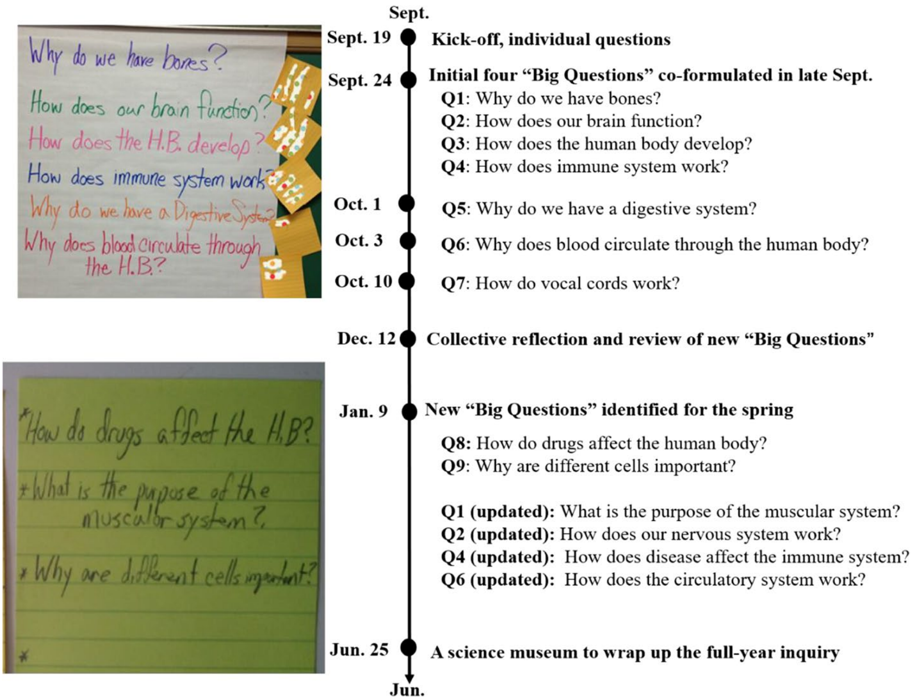


Fig. 1 The chart of "big questions" co-formulated and adapted by the community

and interests generated through the kick-off activity. Mr. S recorded the "big questions" on a chart paper, with students writing down their names next to the related "big question" to trace their personal interests and roles. The chart of "big questions" was hung on the classroom wall to guide students' planning, participation, and reflection. The initial list of inquiry questions was then expanded based on students' initial inquiry in October, with three additional questions formed (see Q5, Q6, and Q7 in Fig. 1). Emergent groups were formed to carry out inquiry and discourse focusing on the new problem areas. With the progress made in each area, students further reflected on their knowledge advances and needs from mid-December to early January (with a holiday break in between). The reflective process led to the emergence of new "big questions" focusing on integrated cross-cutting themes (e.g., Q8 about the impact of drugs and Q9 about cells) as well as the reframing of several existing questions (Q1, Q2, Q4, and Q6) to address deeper issues about the various systems. For example, Q2 "How does the brain function?" was reframed as "How does our nervous system work?". Collaborative groups were reformed based on the modified and reframed inquiry directions for further knowledge building.

The "big questions" that had emerged from students' initial interests and ongoing inquiry were used to guide their collaborative inquiry and discourse. Students collaborated in flexible groups formed and adapted based on emergent goals. They contributed to the discourse in the most relevant areas while also reading and occasionally adding to the discourse in the other areas. We analyzed their online discourse based on the "big questions" to trace how students developed sustained inquiry to address the existing goals while also seeding new directions. Using the date when each "big question" was formally added to the collective chart as a boundary point, we traced students' early-phase conversations seeding the formation of each new "big question" as well as the streams of collaborative discourse to address the "big question" once identified. Table 3 shows the number of student contributors involved in each inquiry area and the number of notes posted before and after the formation of each "big question."

As Table 3 suggests, the initial four questions, especially Q2, Q3, and Q4, led to extensive online discourse among students. Each new emergent "big question" (Q5–Q9) involved a sample of early-phase seed ideas posted as part of the online discourse in related areas. More active online discourse occurred after the community officially added the "big questions" to its collective chart, inviting student contributions in these new areas. Several of the inquiry directions that investigated core and interconnected human body systems, such as Q2, Q3, Q4, Q6, and Q9, involved extensive contributions from almost all students, enabling overlapping collaboration across the boundaries of the different inquiry areas and student groups. Meanwhile, Q8 about drugs only led to limited discourse contributions (seven notes by six students), partly due to the challenging nature of this topic and a lack of resources suitable for fifth graders.

How did students' inquiry moves give rise to transformative changes in the collective inquiry?

Within the above-depicted whole process of the human body inquiry, we conducted deeper analyses of the critical episodes when major changes and adaptions were made to the chart of "big questions." For each episode, our analysis drawn upon classroom observation notes, videos, and artifacts that revealed how students' interactive input supported by the teacher's facilitation led to the structural changes.

(a) The formulation of the initial "big questions" based on student interests. In the kick-off activity, Mr. S selected and showed a short video about the amazing functions of the human body for students. Students watched the video and recorded their personal interests and questions on post-it notes. The teacher then facilitated a whole-class metacognitive meeting to develop collective inquiry goals based on students' interests and questions. Mr. S collected and read the questions to the class. Noticing that some of the questions focused on similar issues, the class decided to cluster the questions based on conceptual themes. Mr. S suggested that students with similar or related questions work as a group to discuss their personal questions and formulate an overarching "big question." The whole class then reconvened for the small groups to share and refine their "big questions." Mr. S encouraged students to offer feedback in return to students who offered them feedback while modeling ways to clarify some of the questions. The teacher recorded the "big questions" on a chart paper (see the image in Fig. 1). He used the metaphor of a "community tree" to describe the collective inquiry. Each "big question" was considered as a branch connected with the overarching goal to understand how the human body works. Students wrote their names next to each question to indicate their interests and commitments. Mr. S also reminded students that they could add more branches to the "community tree" as their inquiry proceeded. The chart of "big questions" was hung on the classroom wall as a guidance to the community. While the above kick-off activity was largely pre-planned by the teacher, the activity served as a context to solicit students' interests and ideas, giving emergence to shared inquiry directions and collaboration structures.

Table 3 The number of notes and contributors before/ after the formation of each "big question"

Inquiry directions framed using "Big Questions"	Early-phase input before the formation of the "big question"		After the formation of the "big question"	
	Notes	Contributors	Notes	Contributors
Q1: Why do we have bones? (later reframed to include the muscular system)	–	–	21	8
Q2: How does our brain function? (later reframed as the nervous system)	–	–	131	24
Q3: How does the human body develop? (including body traits)	–	–	125	24
Q4: How does the immune system work?(later reframed to include diseases)	–	–	194	23
Q5: Why do we have digestive system?	3	3	25	10
Q6: Why does blood circulate through the human body? (later reframed as the circulatory system)	12	11	65	19
Q7: How do vocal cords work?	1	1	25	11
Q8: How do drugs affect the human body?	2	2	7	6
Q9: Why are different cells important?	17	9	60	18

The first four "big questions" were formed at the beginning of the human body inquiry. So they did not have any prior note. A few of the inquiry areas involved more than 22 students because of student changes at various points during the school year, with three students moving away and two new students joining this class

(b) Expanding the chart of "big questions" to accommodate emergent interests of inquiry. With the initial set of "big questions" framing what the community needed to investigate, students with shared interests formed opportunistic groups to conduct inquiry in the focal areas, supported by books and online resources identified by the teacher and his students. Alongside their classroom-based inquiry activities as individuals and in small groups, students posted ideas, information, and questions in KF. A critical episode happened in early October when students reflected on their initial work and pushed for an expanded framing of the community's inquiry directions. In a whole class metacognitive meeting facilitated by Mr. S, with their KF notes projected on a screen, students sat in a circle to discuss the initial progress, thus enabling challenging issues and questions to emerge. Several students pointed out that some of their questions and ideas posted on KF were beyond the scope of the existing "big questions," suggesting that they needed to add new branches to the "community tree." Mr. S acknowledged this need and asked for students to offer proposals. New optional questions and directions were suggested and discussed as part of the classroom work over the subsequent two lesson periods, leading to the formulation of three additional "big questions." These included Q5 regarding the digestive system formulated based on students' notes about food and water, Q6 regarding circulation based on notes posted about heart and blood, and, a bit later, the addition of Q7 focusing on how vocal cords work. Below we analyze the formation of Q7 to understand how a group of students reshaped the community's inquiry directions to include a special inquiry on vocal cords, which is a non-routine topic for their science curriculum.

By early October, the community formulated six "big questions" (Q1–Q6). As students took these up, they formed small flexible groups to conduct collaborative inquiry. A series of somewhat accidental events led to the emergence of Q7 regarding vocal cords. On October 3rd, Oliver (all names are pseudonyms), working on Q3 (human body development), posted a question on KF about how people talk, though this note did not receive much attention. On October 8th, Riley, who volunteered for the Q4 (immune system) inquiry, read a book entitled *Kids InfoBits* (published by Cengage). A section in the book about vocal cords drew her interest. She took some notes in her notebook. On the same day, Julia, who was yet to decide on a "big question," read a magazine called *Science Spin (Primary)*. She took some notes about how sound is produced through air vibration. Mr. S chatted with Julia to understand her inquiry interest and suggested that she start with what she was working on. Sitting next to Julia was Nathan, who had not decided which area to work on yet. Nathan expressed interest in Julia's work. While doing online research using the *BrainPop* video site, Nathan found a video on vocal cords and jotted down notes about how our vocal cords work in his notebook.

In the science lesson on October 10th, Riley, Julia, and Nathan quickly exchanged what they had learned. They then approached Mr. S to talk about their findings and requested to add a new "big question" for their topic. Mr. S called for a short whole-class meeting to introduce their exciting work on vocal cords. The student audience responded positively and agreed that vocal cords could be a new branch beyond the six existing "big questions." Riley, Julia, and Nathan suggested phrasing their question as "How do vocal cords work?" Mr. S added this question to the collective chart of "big questions." The three students then signed their names next to the question to indicate their commitment (see Fig. 2). Later, Caleb, who had signed up for Q4, also expressed his interest in this topic and joined as the fourth member.

After the formulation of Q7 as a branch of the community's inquiry directions, the four group members conducted individual and collaborative inquiry on various issues, including the structure and location of the vocal cords, the manner in which the vocal cords produce

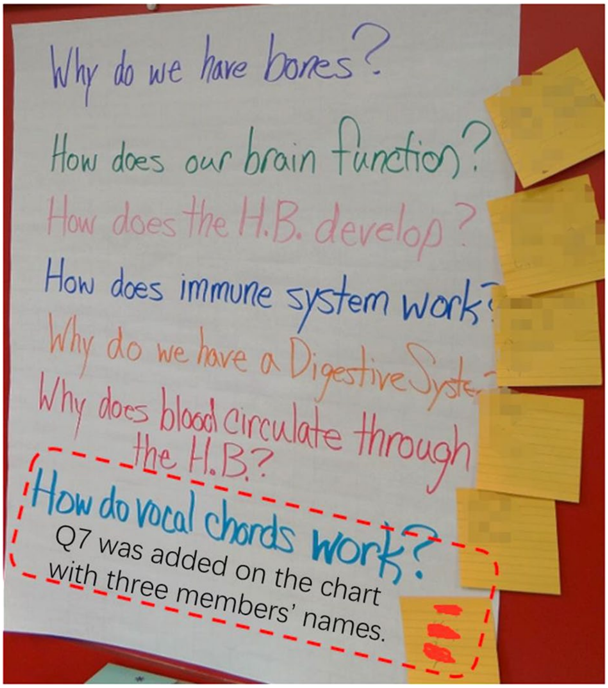


Fig. 2 The addition of Q7 to the collective chart of "Big Question."

sound through vibration, and the way they control the pitch of the voice. They shared their knowledge advances on KF and also responded to the early question asked by Oliver about how people talk. Students who focused on other inquiry areas read their online posts and occasionally shared ideas and questions. For example, Jacob, who was focusing on Q2, asked for more detail about the larynx's role. This question prompted the group members to do more research, with more in-depth knowledge and questions generated around this topic.

Title: Vocal cords by <u>*Riley, Oct 17.*</u>
Vocal cords are the membranes that surround your air tube or larynx. They are located in your throat and are similar to rubber bands because they are very stretchy.
[Build on] **Title: That's something new I didn't know about** by <u>*Jacob, Oct 17*</u>
Your information about the vocal cords [is] very interesting… But could you tell me what the word "larynx" means?
[Build on] **Title: Larynx** by <u>*Riley, Oct 17*</u>
Larynx are the voice box. They are the hollow muscular organ that forms an air passage to the lungs and holding the vocal cords.
[Build on] **Title: Size** by <u>*Maya, Dec 17*</u>
[I need to understand] how big is the larynx? It fits in our body's neck so it must be pretty small. But how small?
[Build on] **When you get older** by <u>*Joseph, Feb 27*</u>
When you get older your larynx might get bigger that how your voice change.

Bella, a member of the Q6 group, read some of these notes and joined in the conversation, asking about the relationship between the thickness of the larynx and the changes of voice at different ages. Meanwhile, Nathan, who was originally a group member of Q7, asked a deeper question: "Vocal cords vibrate to make sounds, but what makes the vocal cords vibrate?" Jayden from the Q3 group responded to share an idea, explaining that fast-moving air rushes through the vocal cords creating the vibration. As reported in Table 3, the online discourse about how vocal cords work eventually involved 25 notes contributed by 11 students.

We interviewed Riley, an initiator of Q7, about her experiences. Reflecting on how the "big questions" helped organize the community's inquiry, she described that it was like "baking a community cake together": The community used the "big questions" to monitor the cake under baking and finding the needed ingredients. Riley recognized that the open questions allowed her to pursue her passion and contribute to the collaborative inquiry: "So I ventured off for that. I decided maybe I'll try that because it's just fascinating. Sometimes you just have that feeling that you like something, and you want to learn about it." The evolving chart of the "big questions" also helped her monitor the flow of inquiry among her peers. "Some people, … like Maya, I think she was like on a direct path. She started with bones. Then she connected bones to the circulatory system, and she made bone marrow… But then there were like other people…like Bella. She started with the circulatory system, but then she ended up with the digestive system, drugs, and food disorders. That's a big leap."

(c) Reframing shared inquiry directions based on updated knowledge and emergent problems. Students worked in and across the seven inquiry areas to advance their understandings from October to early December. New knowledge and questions were shared on KF for online discourse. In a whole-class reflection organized by Mr. S, a set of new questions were raised in the various areas related to "Why the human body can be so flexible?" "How muscles work?" and "How do our five senses work?" and so forth. Another major episode of structure transformation occurred from mid-December to early January (with a holiday break in between) when the teacher and students reviewed their collective progress and identified new problems and directions to further their inquiry. The collaborative reflection was supported by ITM. With the help from Mr. S, students first worked in their small groups to identify important notes related to their focal "big questions." Using ITM, small group members co-identified the keywords for their search, screened the notes found, and added the selected notes to an "idea thread" as a conceptual line of inquiry. Mr. S displayed selected notes with ITM in each idea thread on a timeline to show the temporal progress and further generated a whole class map of the idea threads (see Fig. 3).

Supported by the map of idea threads with ITM projected on a screen by Mr. S, the class discussed their progress and needs. Students noticed that they had more intensive and connected postings in several areas (e.g., brain and digestion), but there were not enough notes in some other threads. Based on their review of the note content and emergent questions in each area, the teacher organized a whole-class meeting to discuss possible ways to deepen their inquiry in the next phase. They identified new and deeper issues to be explored and realized that many of the issues were beyond the scope of the "big questions." With the teacher's input, students in each group then updated their "big question" to reframe their inquiry direction. For example, students working on Q1 (bones) rephrased their focal question from "Why do we have bones?" to "How does the muscular & skeleton system work?" Their new framing applied the new scientific knowledge and language (e.g., "muscular & skeleton system") that they had gained in the inquiry so far. It further accommodated emergent new interests in the community to better understand how muscles work and why the human body can be so flexible. Similarly, students working on Q2 modified their focal question from "How does our brain function?" to "How does the nervous system work?"

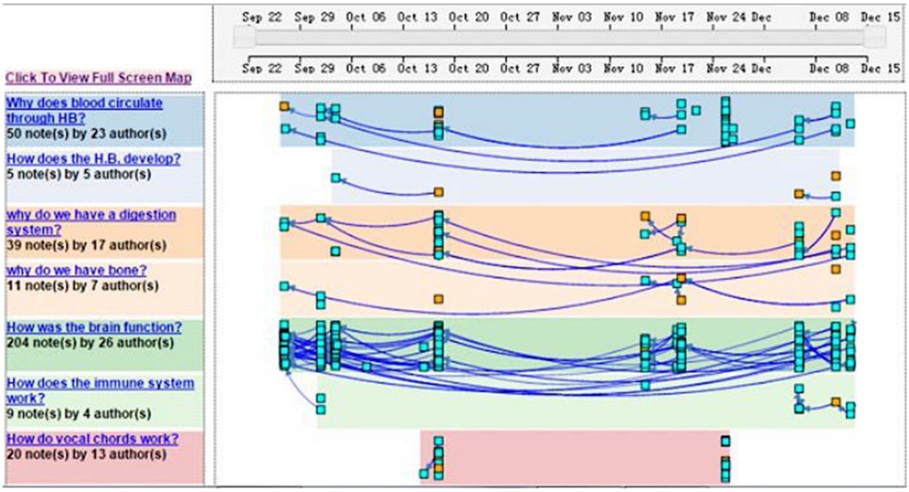


Fig. 3 Seven idea threads organized by students in the ITM-aided reflection. Each color stripe represents an idea thread (a line of inquiry) focusing on a "big question." Each small square in an idea thread shows a note, and an arrowed line connecting two notes shows a build-on connection

recognizing the needs of deeper inquiry about senses, nerves, and the whole nervous system. Q4 was adapted from "How does the immune system work? "to "How does disease affect the immune system?" driven by students' new interests to understand the specific diseases they cared about (e.g., diseases their family members had been diagnosed with). Q6 was also adjusted to highlight the entire circulatory system identified by students.

(d) Formulating "rise-above" conceptual topic at the intersection of multiple streams of inquiry. As part of the reflection to identify new inquiry directions in the middle of the school year, we analyzed the emergence of Q9 about cells, which represents a deep conceptual topic interconnecting the different human body systems. Understandably, the topic about cells was missing from the initial set of inquiry questions generated by the fifth graders, who did not have the knowledge needed to ask questions in this direction. As students investigated the various body systems from October to December, the theme of cells started to emerge in their personal work and collaborative discourse about the specific body systems. In KF, students used the word "cell" frequently in the inquiry of Q6 (blood): Blood is red because of the *red blood cells*, which carry oxygen to every *cell* in your body. At the same time, students working on Q1(bones) posted about the different types of *bone cells* and discussed the interesting role of bone marrow: "bone marrow, which is inside bones, makes most of the body's blood cells." The inquiry about Q4 (immune system) involved an extensive discussion about how *white blood cells* fight germs. The online discourse related to Q2 (brain) mentioned *support cells (glial cells)* that protect *neurons (nerve cells)*. The discussion about Q3 (body development and traits) included notes about *skin cells*, which "are always dying and being replaced."

Mr. S noticed students' emergent interests and ideas related to cells in the different lines of inquiry. In mid-December, he facilitated a reflective discussion in which students shared what they had learned in different areas and their new questions. Many of the questions about the different body systems included the word "cells." Students saw the connection, noting that all questions were about cells, and expressed an interest to better understand cells in the next phase of inquiry. In a follow-up whole class metacognitive meeting in early January, Mr. S asked students to think of a possible "big, juicy question" about cells to guide their collaborative inquiry. Specific questions were first shared, such as "how do glial cells work?" Then students' input moved toward broader framings, such as: What are cells? What are the types of cells? How does each type of cell help the human body? Building on these suggestions, Jayden, a boy from the Q2 group, suggested, "Why are different cells important?" This suggestion received positive responses from peers and was acknowledged by Mr. S, saying: "I kind of like that. And then you can go with all other questions (underneath it). Wow…all those little questions are leading us to a better question… Like someone said, you are not really strapped down by one body system, one question…You really break that rule."

The question of "Why are different cells important?" was added as a "big question" in early January. Given the cross-cutting nature of this new topic, many students working on different body systems were pulled into the inquiry and discourse about cells. They read relevant materials and took notes in their notebooks using "Cells" as a new subject label to organize their notebooks. They also contributed to the classroom and online discussions and designed models and posters. As Table 3 reports, 18 students contributed 60 notes in the collaborative conversation about cells with connections to their previous focal areas. For example, Maya, a girl working on Q1 (bones), joined the newly formed group. She shared her understanding and further raised a deeper question: "My theory is that bones are also made of cells. Some bone cells are star shaped. How many different types of bone cells are there and what do they look like?" A number of students continued investigating the different types of cells related to the various body systems, while several others discussed issues about the cells themselves, including their structural parts and functions and different types. We conducted qualitative analysis of the KF notes to identify the key questions and understandings generated by students about cells as related to specific body systems. Figure 4 summarizes the results, showing the extensive conceptual connections developed by the community.

From January to May, students continued their personal and collaborative inquiry guided by the updated "big questions." Each area involved a group of core students and other occasional contributors who were simultaneously working on other related problems. Students also had the freedom to shift their main foci based on their evolving interests and connections. Another collaborative reflection session was organized by Mr. S in late May. Each area's core members used ITM to select and review the important notes related to their "big question," which were organized as an idea thread. Figure 5 shows the collective map of idea threads organized by students. Two of the areas related to Q2 and Q4 respectively each had two idea threads set up to reflect on the discourse on sub-topics (e.g., diseases and immune system for Q4). Mr. S projected the new idea thread map on a screen. Reflecting on their progress, students were impressed by the extensive build-on connections revealed in each idea thread, spreading across different periods and inquiry areas. Following the reflection, students further wrote reflective notes ("journey of thinking") to reflect on what they had learned and what they still needed to clarify in preparation for the final event for cross-classroom exchange.

To what extent did such dynamically organized processes support productive knowledge building?

For this research question, we conducted social network analysis and content analysis of online discourse and analyzed student responses in the pre-and post-test.

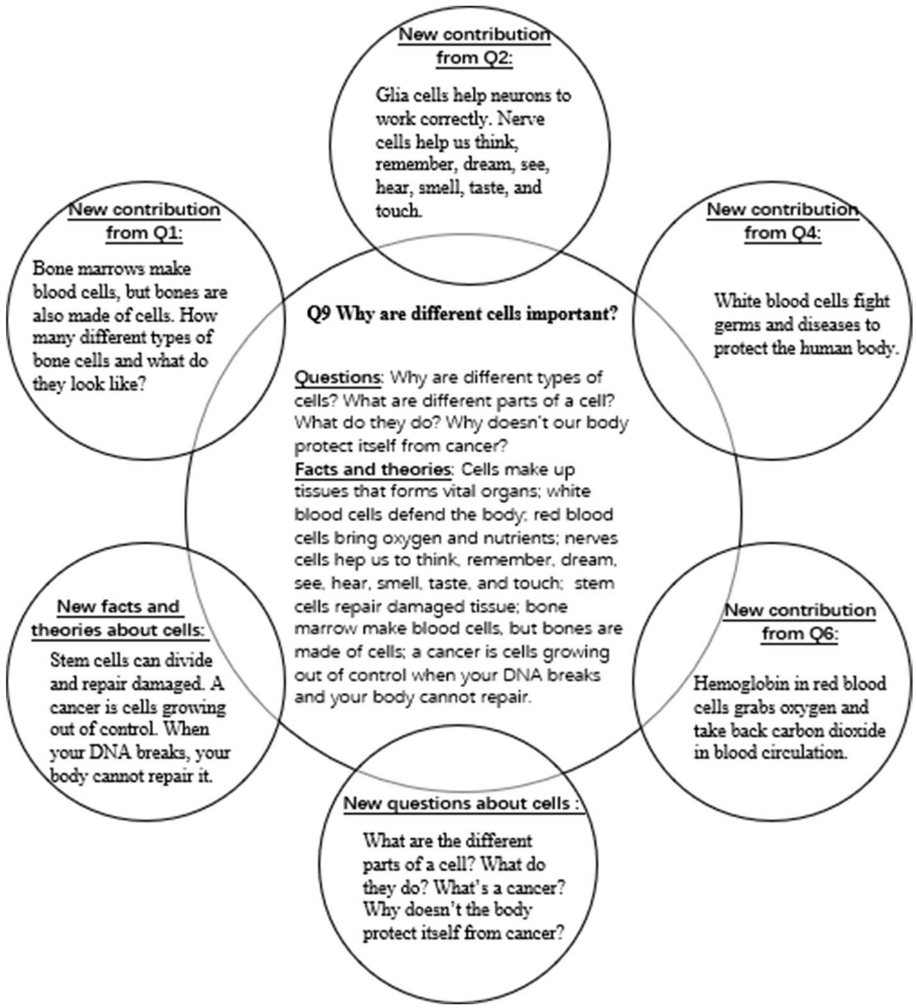


Fig. 4 A summary of students' understandings and questions generated in the inquiry of cells as related to the other inquiry areas

Social network analysis of online discourse

We analyzed student online discourse entries during the school year, considering the reorganization of the "big questions" in early January (January 9th) as the midpoint of the whole inquiry. Students posted a total of 667 notes. On average, each student posted 31.76 notes, including 11.76 before and 20 notes after the mid-year reorganization. Social network analysis was conducted to examine who had built on whose notes in the online discourse. In Table 4, we report the primary measures of analysis. Figure 6 shows the sociograms of student interactions in the first and second half of the inquiry. The label of each node (student) in Fig. 6 also indicated the "big question" area(s) that the student had focused on. Overall, students developed extensive build-on connections with their peers, with the density and degree of social contact further increased after the reorganization of

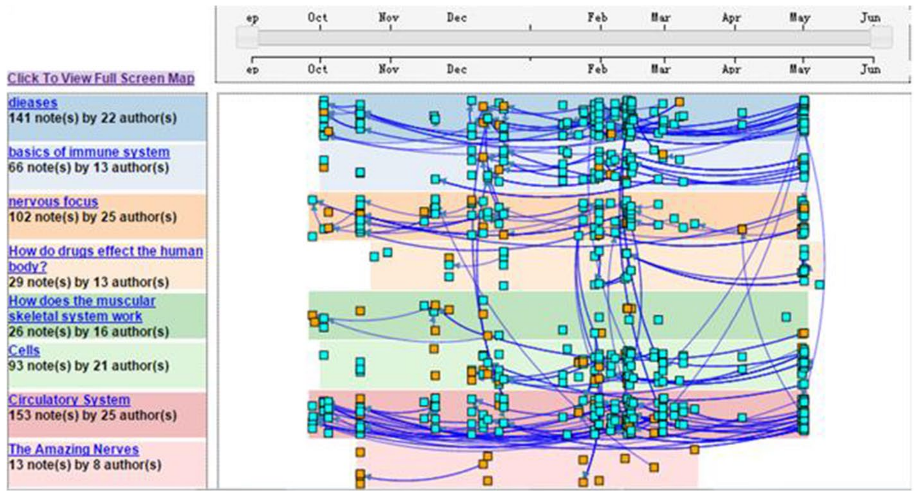


Fig. 5 Idea threads organized by students in the second ITM-aided reflection. Each color stripe represents an idea thread (a line of inquiry). Each small square in an idea thread shows a note, and an arrowed line connecting two notes shows a build-on connection

Table 4 Social network analysis of student interactions in Knowledge Forum

Period	Nodes	Edges	Graph density	Degree	Closeness centrality	Between-ness centrality
1st half	22	119	0.26	10.82	0.51	20.00
2nd half	24	202	0.37	16.83	0.60	13.62

the community's inquiry. Most of the students worked on more than one inquiry area each. They developed build-on connections with peers who worked on the same area(s) and those who focused on other areas, with broader (more expansive) connections formed in the second half of the inquiry after the reflective reorganization.

Content analysis of online discourse

Table 5 reports our content analysis of student notes based on contribution types, including questioning, theorizing and explaining, incorporating evidence, referencing sources, and connecting and integrating ideas. In the first half of the inquiry, a majority of student notes shared questions (37.25%) and personal theories/explanations (37.65%). In the second half of the inquiry, students had more notes generating personal theories and explanations (50.71%) supported by using information sources (21.90%) while posing questions, incorporating evidence, and connecting the different concepts and topics for integrated understanding.

Further content analysis was conducted for the two most extensive contribution types: questioning and theorizing/explaining. As Table 6 indicates, in the first half of the human body inquiry, students asked a large number of explanation-seeking questions that represented their initial wonderings within each "big question" area, such as "How do vocal

Fig. 6 The sociograms of student interactions in the 1st half (**a**) and 2nd half (**b**) of the yearlong inquiry ▶

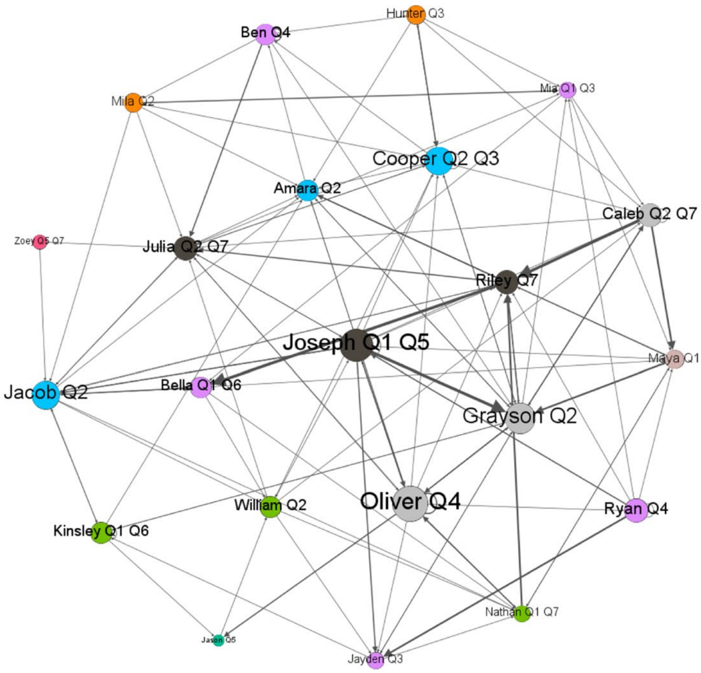
cords function?" In the second half of the inquiry, students raised an equivalent amount of fact-seeking and explanation-seeking questions, primarily for deepening existing inquiry topics and ideas. For example, Nathan asked: "Vocal cords vibrate to make sounds but what makes the vocal cords vibrate?" The second half of the inquiry also revealed more questions addressing connections between two or more body systems as opposed to single area questions. For example, Mila, who was working on Q2 (brain), commented on a note about vocal cords (Q7): "WOW! Julia, I never knew…the vocal cords. Really nice job. I didn't even know that the vocal cords could get DISEASES!!! And Julia, how do you get diseases?" The question about how the vocal cords may suffer from disease created a connection between Q4 and Q7.

To further gauge students' idea improvement in the interactive inquiry and discourse, we traced their notes that offered personal explanations, which were coded based on four levels of scientific sophistication (from 1 pre-scientific to 4 scientific). As noted above, the purpose of the knowledge building discourse was not for students to only share "correct" ideas that they felt sure about but to take the risk to explore issues of uncertainty and propose tentative ideas (and guesses) for peers to continually improve upon. As a whole, the average rating of student explanations was 2.49 for the first half of the human body inquiry (till early January, $n = 93$) and 2.62 for the second half of the inquiry ($n = 213$).

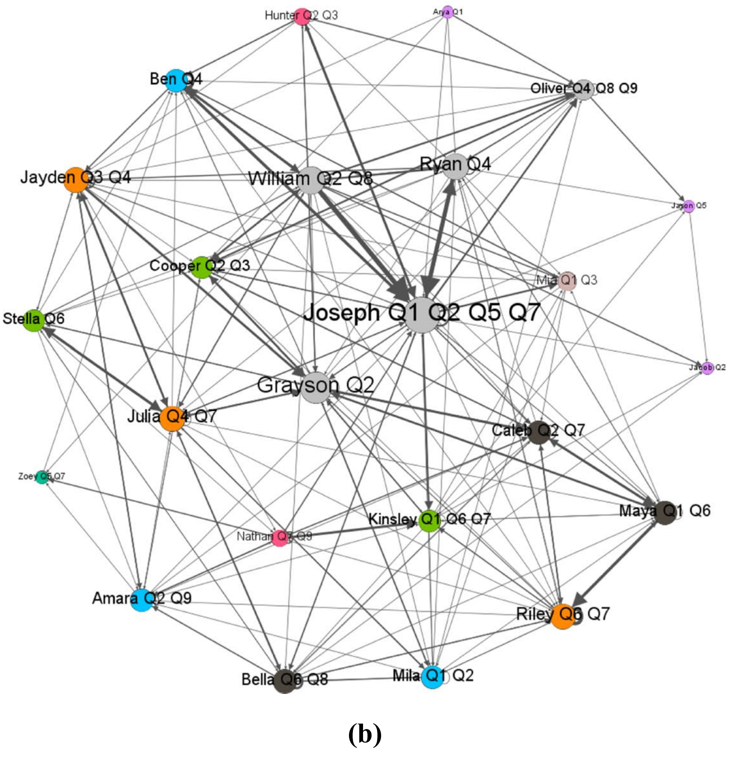
For a more detailed view of student idea improvement, we examined how their explanations changed over time in each of the "big question" areas. For the feasibility of cross-time comparison, the analysis focused on the "big question" areas with extensive online discourse, each involving more than 20 notes offering personal explanations. Based on this criterion, we selected Q2, Q3, Q4, and Q6. The four lines of inquiry had a total of 252 notes that shared personal understandings. For the notes in the four areas, we first sequenced the notes based on the time of creation and then divided the notes into four "phases," each having an equivalent proportion of notes. Table 7 reports the mean scientific rating of students' explanations across the four phases in each line of inquiry. A one-way ANOVA analysis comparing the average scientific sophistication levels of ideas suggests a significant improvement across the four phases ($F(3, 248) = 12.48$, $p < .001$, $\eta^2 = .13$). Post-hoc comparisons using the least significant difference (LSD) test indicated significantly higher ratings for Phase 4 ($p < .001$, Cohen's $d = 1.04$) and Phase 3 ($p < .001$, Cohen's $d = .64$) than Phase 1, for Phase 4 ($p < .001$, Cohen's $d = .77$) and Phase 3 ($p < .05$, Cohen's $d = .36$) than Phase 2, and for Phase 4 than Phase 3 ($p < .05$, Cohen's $d = .36$). These results suggest that students were able to improve their understandings toward a more scientific account.

Analysis of individual student understanding based on the pre-and post-test

We graded student responses to each question based on two measures: level of scientific sophistication (1—pre-scientific to 4—scientific) and exploratory coherence (from 1—describing the body parts involved, to 2—explaining the processes based on a single system, and 3—integrated explanations involving multiple systems). The average scientific rating of student answers was 1.43 ($SD = 0.63$) for the pre-test and 2.99 ($SD = 0.78$) in the post-test, with a significant difference as revealed by a paired sample t-test ($t(13) = -7.61$, $p < .001$). Students' understandings improved from between "1—pre-scientific" and "2—hybrid" to close to "3—basically scientific." Besides, the rating of ideas based on explanatory coherence also improved from the pre-test ($M = 0.98$, $SD = 0.53$) to the post-test


Hunter Q3
Ben Q4
Mia Q1 Q3
Mila Q2
Cooper Q2 Q3
Amara Q2
Caleb Q2 Q7
Zoey Q5 Q7
Julia Q2 Q7
Riley Q7
Joseph Q1 Q5
Maya Q1
Jacob Q2
Bella Q1 Q6
Grayson Q2
Oliver Q4
Ryan Q4
William Q2
Kinsley Q1 Q6
Nathan Q1 Q7
Jason Q5
Jayden Q3

(a)


Hunter Q2 Q3
Arya Q1
Ben Q4
Oliver Q4 Q8 Q9
Jayden Q3 Q4
William Q2 Q8
Ryan Q4
Jason Q5
Cooper Q2 Q3
Mia Q1 Q3
Stella Q6
Joseph Q1 Q2 Q5 Q7
Jacob Q2
Grayson Q2
Julia Q4 Q7
Caleb Q2 Q7
Zoey Q5 Q7
Kinsley Q1 Q6 Q7
Maya Q1 Q6
Nathan Q7 Q9
Amara Q2 Q9
Riley Q6 Q7
Bella Q6 Q8
Mila Q1 Q2

(b)

Table 5 The number and percentage of different discourse moves in Knowledge Forum

Period	Questioning	Explaining	Evidence	Referencing sources	Connecting & integrating
1st half	92 (37.25%)	93 (37.65%)	15 (6.07%)	43 (17.41%)	4 (1.62%)
2nd half	69 (16.43%)	213 (50.71%)	32 (7.62%)	98 (21.90%)	14 (3.33%)

($M=2.29$, $SD=0.53$), with a significant difference ($t(13)=-10.56$, $p<.001$). Their initial responses were close to 1, focusing on body parts without process-based explanation. In the post-test, students' ideas were rated between 2 (explanation of processes based on one body system) and 3 (integrated explanation of how multiple systems work together). For example, in the test, a question asked students to explain how the body parts worked together to help Jack avoid a possible burn. Grayson responded in the pre-test with a drawing mentioning merely the hand and arm. He explained: "Jack's hand felt the heat from the stove and once he realized that the stove was hot, he pulled his hand away from the stove." However, in the post-test, Grayson drew a picture involving the nervous system, muscles, hand, and skin and provided a detailed explanation of nervous system control and hand movement. "The nerves in the skin felt the heat and sent the message to pull away up to the brain. The message travelled through the nerves and up the brain stem to the brain. The reflex kicked on and the muscles pulled away."

Discussion

This research investigated how students and their teacher worked together to co-configure knowledge building practices through reflective structuration and transformation, focusing on students' epistemic agency for deepening, expanding, and re-organizing shared inquiry directions. We discuss a few insights gained through the data analyses.

Dynamic, ever-deepening inquiry can be co-configured and regulated through reflective structuration and transformation

The data analysis generated an elaborated account of how students and their teacher co-configured their unfolding pathways of inquiry over a whole school year. The evolving chart of "big questions" served as a publicly shared structure-bearing resource (Sewell, 1992) that signified collective inquiry directions. This co-constructed structure played a social regulation role in framing and reframing what students needed to investigate over time, guiding individual focus of inquiry, and facilitating the emergence and adaptation of collaborative groups. An initial set of four "big questions" was co-formulated based on student personal interests and questions. These "big questions" guided students' initial inquiry and discourse in which new ideas, questions, and connections were constructed. Responding to the emergent changes, the community went through a series of structural elaboration and modifications. The "big questions" were expanded and adapted to accommodate new directions, reframe existing inquiries in light of new understanding, and formulate cross-cutting themes at the intersection of the different body systems (see Fig. 1).

Table 6 The number and percentage of different types of questions posted in the 1st and 2nd half of the human body inquiry

Period	Dimension a		Dimension b		Dimension c	
	Fact seeking	Explanation seeking	Initial wondering	Idea deepening	Single-area question	Cross-area question
1st half	22 (23.91%)	70 (76.09%)	66 (71.74%)	26 (28.26%)	85 (92.39%)	7 (7.61%)
2nd half	9 (13.04%)	60 (86.96%)	22 (31.88%)	47 (68.12%)	56 (81.16%)	13 (18.84%)

Table 7 The scientific ratings of student explanations over time (focusing on Q2, Q3, Q4, and Q6)

Measures	Phase 1	Phase 2	Phase 3	Phase 4
Mean	2.46	2.68	2.94	3.19
SD	.76	.69	.74	.64
n	63	63	63	63

The co-constructed "big questions" represented by classroom artifacts served as a public reference framework to guide students' joint attention, participation, and reflection. Individually, students signed their names next to the "big question(s)" to position their personal contribution in the context of the community's inquiry. At the small group and community level, opportunistic groups formed based on students' shared and evolving interests. Students reflected on unfolding lines of inquiry and knowledge progress in the community with the support of the ITM tool, monitoring the emergence of new inquiry directions and connections. Such reflection enhanced students' personal and collaborative efforts to address their community's evolving goals, leading to extensive knowledge building discourse focusing on the core problem areas (Table 3). The social network analysis revealed expansive and opportunistic connections among the students (Fig. 6). They not only built on the ideas of their close peers who worked on the same "big questions" but also those working on broader areas, rendering dynamic information flows and idea contact that are needed for transformative inquiry practices.

Reflective structuration and transformation provide a temporal and relational context for students to enact epistemic agency with the teacher's support

The data analysis documented students' interactive, agentic moves to monitor emerging interests and needs in their inquiry and participate in reflective conversations with their peers and the teacher to expand, reframe, and re-organize the directions of the community's inquiry. These actions gave emergence to new/modified inquiry directions and collaboration structures over time, with students taking on increasing control. Combining findings from this and our previous work (Tao & Zhang, 2018), we summarize the interactive input from the teacher and students to co-configure and adapt their collective inquiry (see Table 8).

Specifically, the whole inquiry started with a kick-off activity designed by the teacher, taking into account the school's curriculum requirements, prior science teaching and learning practices, and the changes needed to implement knowledge building. The kick-off activity served to elicit diverse interests, ideas and wonderments as the input to shared metacognitive processes for building shared inquiry directions, which were represented using the chart of "big questions." Students worked with the initial structures to start open exploration and co-constructed new/elaborated structures as their inquiry proceeded. The teacher was an attentive listener and observer working to understand students' diverse ideas, questions, and new progress across individual and collaborative settings. He facilitated reflective conversations about evolving goals and inquiry strategies, including ways to address student needs for resources and support. Together, they engaged in reflectively capturing emergent directions, connections, and patterns of inquiry as they created/adapted shared structures accordingly. New "big questions" were added (e.g., Q5, Q6, and Q7), existing directions were reframed, and cross-cutting inquiry themes emerged (e.g., Q9), thus leading to an ongoing reconfiguration of student

Table 8 Interactive input to co-configure and adapt collective inquiry

Changes/adaptions	Teacher input	Student input
Formulate initial "big questions" based on student interests	Identify the science area for inquiry based on the school's curriculum Prepare kick-off activities and resources Facilitate a whole class metacognitive meeting to share personal questions and frame shared "big questions" Create public representations of co-generated "big questions"	Participate in kick-off activities to experience the topic of inquiry Take notes of initial interests, questions and ideas Participate in metacognitive meetings to share personal questions, reflect on connections, and formulate "big questions" Make personal commitments and form groups based on the chart of "big questions"
Expand and reframe shared inquiry directions over time based on emergent interests/needs and knowledge progress	Follow student inquiry and discourse in the co-generated problem areas Facilitate small group and whole class meetings to share new progress and questions, create new "big questions" or reframe existing ones Update shared representations of inquiry directions and groups	Conduct individual and collaborative inquiry guided by the "big questions" Reflect on inquiry progress toward shared goals while recognizing emergent gaps and opportunities Participate in metacognitive meetings to form new "big questions" or reframe existing ones Adapt personal inquiry focus and groups in light of changing directions
Formulating "rise-above" topics at the intersection of multiple streams of inquiry	Take notice of emergent idea connections in student discourse Facilitate student exchanges across areas Facilitate reflective review and mapping of "big ideas"	Mutual learning of new knowledge and questions across areas Reflect on connective concepts and "big ideas" Reframe inquiry questions and directions in light of the connective concepts and "big ideas" Adapt personal inquiry focus and groups accordingly

participation and collaboration. The co-constructed inquiry structures, such as the "big questions," then provided a referential frame for the teacher and students to monitor the ongoing flow of ideas in their community, plan for deeper inquiry, and make accountable contributions. At the same time, the frame is not fixed but remains open for students' creative input, as they had the opportunity to expand and reframe the landscape of their collective work and adjust their personal roles. With the expansive framing of ever-deepening inquiry, they could grapple with new challenges and develop new lines of work, including non-routine science topics such as vocal cords; leverage emergent connections across the different areas to work on integrative rise-above concepts (e.g., cells); and reform group structures as needed. Supporting students to enact such transformative agency is essential to dynamic knowledge building that continually unfolds over time, thus breaking traditional classroom barriers and curriculum boundaries. On a related note, such agency is also essential for enhancing equitable participation, as it gives students the power to work as co-designers of their learning pathways and respective futures (Gutierrez & Barton, 2015).

Co-configured dynamic inquiry practices enable productive knowledge building interactions and outcomes

The analyses suggest that the co-configured dynamic inquiry practices enabled productive knowledge building processes and outcomes. Students made active and continual contributions to the collaborative discourse related to the core "big questions" (Table 3), with extensive connections built among students including those who worked on different areas (Fig. 6). Their online discourse integrated a diverse range of epistemic contributions with progressive questioning and explaining as two core moves (Table 5). Students continually asked deeper questions as the inquiry progressed, pushing the boundary of their knowledge to seek further facts and explanations, initiate new problems while deepening their inquiry of the existing ones, and search for cross-area connections over time, especially in the second half of the inquiry (Table 6). The dynamic inquiry process enabled continual improvement of ideas toward deeper and more coherent understandings, as gauged based on the content analysis of the collaborative discourse (Table 7) and individual assessments. These findings are consistent with the results of our recent research conducted in other classrooms (Tao & Zhang, 2018; Zhang et al., 2018). Students co-constructed structures in the form of shared directions and research cycles to organize and guide collaborative inquiry, leading to productive knowledge building.

This study has a few limitations. First, as noted above, the pre- to post-test comparison was based on a small sample of 13 students who took both tests. Second, this study, which focused on understanding students' agentic participation, did not make systematic analysis of the teacher's ongoing planning and scaffolding. A more detailed analysis of teacher support for shared structure building can be found in our previous analysis (Tao & Zhang, 2018), with deeper studies underway to trace and support teachers' ongoing noticing of classroom dynamics and emergent planning (Park & Zhang, 2020; Tao & Zhang, 2021). Third, the findings reported here were based on students' inquiry work in a single classroom in one content area. In the larger design-based research project, we have been testing using reflective structuration to organize student-driven knowledge building in other interdisciplinary areas (e.g., ecosystems and environment) in a network of classrooms.

Conclusions and implications

Creative and transformative CSCL practices require agentic and dynamic forms of learning regulation and classroom design. The results of this study elaborate reflective structuration and transformation as a socio-epistemic mechanism for co-configuring dynamic inquiry practices that unfold over long periods of time, with students taking on high-level agency. Building on our previous work (Tao & Zhang, 2018; Zhang et al., 2018), the findings suggest that students as young as fifth graders can work as epistemic agents to co-construct shared inquiry structures while continually deepening their knowledge in a domain area.

In this study, students co-constructed an evolving chart of "big questions" as their inquiry proceeded: to co-identify shared directions of inquiry based on their initial interests, expand a list of "big questions" to accommodate emergent interests, reframe shared directions based on knowledge progress, and formulate cross-cutting themes at the intersection of the different areas. The chart of "big questions" as an emergent structure represented the community's evolving goals and directions, serving to guide members' *intention* and *attention* as they navigated dynamic flows of knowledge within their community. Students monitored emergent ideas and opportunities, took responsive inquiry actions and discourse moves, and developed flexible small groups and idea connections. Whereas pre-defined structures tend to limit student agency, the emergent progress to co-construct shared inquiry structures leverages students' epistemic agency for continually advancing their knowledge practices beyond the status quo (Scardamalia & Bereiter, 2014). Students not only direct and regulate their efforts in the preset scope and structures but also reshape and transform the landscape of their collective work in response to emergent interests and opportunities. Such personal and collective agency is critically needed for students to navigate the white-water world and influence it (Pendleton-Jullian & Brown, 2018).

Reflective structuration offers new strategies for classroom regulation/orchestration of dynamic CSCL and knowledge building. Different from traditional prescriptive designs, reflective structuration of knowledge building practices leverages "designing for emergence" (Pendleton-Jullian & Brown, 2018): to recognize the socio-ecological constraints of the classroom and introduce a context for exploratory inquiry and participation, then discover emergent trails of inquiry (e.g., high-potential interests and ideas, social roles and relationships) upon which productive pathways of inquiry and participation may be co-constructed, thereby reconfiguring the context of inquiry, which in turn opens up new possibilities of creative inquiry and participation (Zhang et al., 2018). While a whole inquiry may have its overarching goal and time frame, the evolving directions of what students should investigate and the overall shape of the inquiry are driven by students' shared interest emerged from ongoing collaborative inquiry, guided by the core values and principles of the community, such as the principles of knowledge building (Scardamalia, 2002; Zhang et al., 2011). Reflective structuration provides a socio-epistemic mechanism to translate the principles into knowledge building practices. Core principles are translated into daily flows of knowledge building activities as classroom members co-construct shared framing of their joint inquiry as it unfolds, including what they should investigate, how, and by/with whom.

Drawing upon the insights gained from this and other studies, our team has been upgrading the ITM tool to support dynamic knowledge building practices. Learning analytics are integrated to provide reflective feedback on emerging inquiry directions, idea progress, and connections. Future studies will explore ITM-supported interventions to catalyze dynamic knowledge building in broader classrooms and support teachers' improvisational scaffolding in this context.

Acknowledgements This research was supported by the U. S. National Science Foundation (#1122573, #1441479 awarded to the second author) and the China Postdoctoral Science Foundation (# 2019M660522 awarded to the first author). We owe special thanks to the teacher and students for their creative work enabling this research, and to Dr. Mei-Hwa Chen and her team for their work on software development. We also extend our gratitude to the editors and reviewers who provided constructive feedback and suggestions. Part of the analysis was presented at the International Conference of Computer-Supported Collaborative Learning (2015, Gothenburg, Sweden).

References

Archer, M. S. (1982). Morphogenesis versus structuration: On combing structure and action. *British Journal of Sociology, 33*, 455–483.

Bereiter, C., & Scardamalia, M. (2014). Knowledge building and knowledge creation: one concept, two hills to climb. In S. C. Tan, H. J. So, & J. Yeo (Eds.), *Knowledge creation in education* (pp. 35–52). Springer.

Carolan, B. V. (2014). *Social network analyses and education: Theory, methods & applications*. SAGE.

Chi, M. T. H. (1997). Quantifying qualitative analyses of verbal data: A practical guide. *Journal of the Learning Sciences, 6*, 271–315.

Cress, U., Oshima, J., Rosé, C., & Wise, A. (in press). Foundations, processes, technologies, and methods: An overview of CSCL through its handbook. In Cress, U., Oshima, J., Rosé, C., & Wise, A. (Eds.), *International handbook of computer-supported collaborative learning*. Springer.

Damsa, C. I., Kirschner, P. A., Andriessen, J. E., Erkens, G., & Sins, P. H. (2010). Shared epistemic agency: An empirical study of an emergent construct. *Journal of the Learning Sciences, 19*(2), 143–186.

Damşa, C. I., Nerland, M., & Andreadakis, Z. E. (2019). An ecological perspective on learner-constructed learning spaces. *British Journal of Educational Technology, 50*(5), 2075–2089.

Derry, S. J., Pea, R. D., Barron, B., Engle, R. A., Erickson, R. A., Goldman, F., et al. (2010). Conducting video research in the learning sciences. *Journal of the Learning Sciences, 19*, 3–53.

Engeström, Y. (2008). *From teams to knots: Activity-theoretical studies of collaboration and learning at work*. Cambridge University Press.

Engle, R. A., Lam, D. P., Meyer, X. S., & Nix, S. E. (2012). How does expansive framing promote transfer? Several proposed explanations and a research agenda for investigating them. *Educational Psychologist, 47*(3), 215–231.

Giddens, A. (1984). *The constitution of society*. Polity Press.

Gloor, P. A. (2006). *Swarm creativity: Competitive advantage through collaborative innovation networks*. Oxford University Press.

Goodwin, C. (2017). *Co-operative action*. Cambridge University Press.

Goodyear, P., & Dimitriadis, Y. (2013). "In medias res": Reframing design for learning. *Research in Learning Technology, 21*, 1–13. https://doi.org/10.3402/rlt.v21i0.19909

Gutierrez, K. D., & Barton, A. C. (2015). The possibilities and limits of the structure–agency dialectic in advancing science for all. *Journal of Research in Science Teaching, 52*(4), 574–583.

Hagel, J., Brown, J. S., & Davison, L. (2010). *The power of pull: How small moves, smartly made, can set big things in motion*. Basic Books.

Hakkarainen, K. (2009). A knowledge-practice perspective on technology-mediated learning. *International Journal of Computer-Supported Collaborative Learning, 4*, 213–231.

Järvelä, S., & Hadwin, A. F. (2013). New frontiers: Regulating learning in CSCL. *Educational Psychologist, 48*(1), 25–39.

Järvelä, S., Järvenoja, H., & Malmberg, J. (2019). Capturing the dynamic and cyclical nature of regulation: Methodological progress in understanding socially shared regulation in learning. *International Journal of Computer-Supported Collaborative Learning, 14*, 425–441.

Järvelä, S., Kirschner, P. A., Hadwin, A., Järvenoja, H., Malmberg, J., Miller, M., & Laru, J. (2016). Socially shared regulation of learning in CSCL: Understanding and prompting individual- and

group-level shared regulatory activities. *International Journal of Computer-Supported Collaborative Learning, 11*(3), 263–280.
Johnson, S. (2001). *Emergence: The connected lives of ants, brains, cities, and software*. Scirbner.
Kirschner, P. A., & Erkens, G. (2013). Toward a framework for CSCL research. *Educational Psychologist, 48*(1), 1–8.
Kali, Y., McKenney, S., & Sagy, O. (2015). Teachers as designers of technology enhanced learning. *Instructional Science, 43*(2), 173–179.
Miller, E., Manz, E., Russ, R., Stroupe, D., & Berland, L. (2018). Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards. *Journal of Research in Science Teaching, 55*(7), 1053–1075.
Park, H., & Zhang, J. (2020). *Teachers' reflective noticing and responsive scaffolding to support student knowledge building in Grade 5 science*. Annual Meeting of American Educational Research Association: San Francisco.
Pendleton-Jullian, A. M., & Brown, J. S. (2018). *Design unbound: Designing for emergence in a white water world*. The MIT Press.
Perkins, D. N., Jay, E., & Tishman, S. (1993). Beyond abilities: A dispositional theory of thinking. *Merill-Palmer Quarterly, 39*(1), 1–21.
Rogat, T. K., & Linnenbrink-Garcia, L. (2011). Socially shared regulation in collaborative groups: An analysis of the interplay between the quality of social regulation and group processes. *Cognition and Instruction, 29*(4), 375–415.
Roschelle, J. (2020). A review of the international handbook of computer-supported collaborative learning. *International Journal of Computer-Supported Collaborative Learning, 15*, 499–505.
Sawyer, R. K. (2005). *Social emergence: Societies as complex systems*. Cambridge University Press.
Sawyer, R. K. (2007). *Group genius: The creative power of collaboration*. Cambridge University Press.
Sawyer, R. K. (2015). A call to action: The challenges of creative teaching and learning. *Teachers College Record, 117*(10), 1–34.
Scardamalia, M. (2002). Collective cognitive responsibility for the advancement of knowledge. In B. Smith (Ed.), *Liberal education in a knowledge society* (pp. 67–98). Open Court.
Scardamalia, M., & Bereiter, C. (1991). Higher levels of agency for children in knowledge building: A challenge for the design of new knowledge media. *Journal of the Learning Sciences, 1*(1), 37–68.
Scardamalia, M., & Bereiter, C. (2014). Knowledge building and knowledge creation: theory, pedagogy, and technology. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (2nd ed., pp. 397–417). Cambridge University Press.
Sewell, W. H., Jr. (1992). A theory of structure: Duality, agency, and transformation. *American Journal of Sociology, 98*, 1–29.
Siqin, T., van Aalst, J., & Chu, S. K. W. (2015). Fixed group and opportunistic collaboration in a CSCL environment. *International Journal of Computer-Supported Collaborative Learning, 10*(2), 161–181.
Tao, D., & Zhang, J. (2018). Forming shared inquiry structures to support knowledge building in a grade 5 community. *Instructional Science, 46*, 563–593.
Tao, D., & Zhang, J. (2021). *Implementing emergent design to support agency-driven knowledge building practices in a Grade 5 science classroom*. Paper presented at the Annual Meeting of American Educational Research Association: Orlando.
Varelas, M., Tucker-Raymond, E., & Richards, K. (2015). A structure-agency perspective on young children's engagement in school science: Carlos's performance and narrative. *Journal of Research in Science Teaching, 52*(4), 516–529.
Wise, A. F., & Schwarz, B. B. (2017). Visions of CSCL: Eight provocations for the future of the field. *International Journal of Computer-Supported Collaborative Learning, 12*, 423–467.
Zhang, J. (2013). *Foster a self-sustained, collective trajectory of inquiry through adaptive collaboration.* Paper presented at the Annual Meeting of American Educational Research Association: San Francisco.
Zhang, J., & Chen, M.-H. (2019). Idea thread mapper: designs for sustaining student-driven knowledge building across classrooms. In K. Lund, G. Niccolai, E. Lavoué, C. Hmelo-Silver, G. Gweon, & M. Baker (Eds.), *A wide lens: Combining embodied, enactive, extended, and embedded learning in collaborative settings, 13th International Conference on Computer Supported Collaborative Learning (CSCL) 2019* (Vol. 1, pp. 144–151). Lyon: International Society of the Learning Sciences.
Zhang, J., Hong, H.-Y., Scardamalia, M., Teo, C., & Morley, E. (2011). Sustaining knowledge building as a principle-based innovation at an elementary school. *Journal of the Learning Sciences, 20*, 262–307.

Zhang, J., Scardamalia, M., Lamon, M., Messina, R., & Reeve, R. (2007). Socio-cognitive dynamics of knowledge building in the work of nine- and ten-year-olds. *Educational Technology Research and Development, 55*, 117–145.

Zhang, J., Scardamalia, M., Reeve, R., & Messina, R. (2009). Designs for collective cognitive responsibility in knowledge building communities. *Journal of the Learning Sciences, 18*, 7–44.

Zhang, J., Tao, D., Chen, M.-H., Sun, Y., Judson, D., & Naqvi, S. (2018). Co-organizing the collective journey of inquiry with idea thread mapper. *Journal of the Learning Sciences, 27*, 390–430.