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Collaborative design of a simulation-based math classroom: Contradictions and solutions between teaching and research

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Abstract: Although co-design between teacher and researcher as a means could effectively promote teachers' professional development, little is known about the process of developing a simulation-based math classroom for compulsory education by a co-design team between teachers and researchers. From a dual theoretical perspective involving activity theory and boundary crossing, we investigate the contradictions that emerged between teaching and research activity systems, and the way to deal with the contradictions. The results showed three main contradictions: (1) theoretical ideas versus practical knowledge, (2) simulation-based versus traditional teaching design, and (3) generative interactions versus structured classroom culture. The contradictions were resolved to varying degrees through the efforts of participants who acted as brokers, mainly in terms of the process of perspective making and taking. These findings not only guide how to maximize learning opportunities for teachers in the co-design process with researchers but also enrich teacher education and activity theory.

Keywords: Activity system, contradiction, boundary crossing, math classroom design, mathematics education research

1. Introduction

The increase in digital technologies and teaching tools has placed higher requirements on teachers' professional capabilities to integrate technology into classroom practice. The collaborative design between teachers and researchers has the potential to improve teachers' teaching expertise and refine instructional practice by combining the unique expertise of both teachers and researchers (Cai et al., 2017). Due to the different cultural backgrounds of the co-design members, it is common for contradictions to arise in cooperation (Qi et al., 2022). Properly handled contradictions could cause teachers and researchers to critique existing practices or experiences and make an effort to explore new solutions, which in turn can lead to innovation (Yan & Yang, 2019).

In traditional K-12 math classroom teaching, students tend to be polarized in their understanding of mathematical relationships. Some students may struggle with grasping these fundamental principles. Digital classrooms that include interactive simulations are particularly valuable in math teaching and learning (Moeller et al., 2015), especially for internalizing the understanding of complex mathematical concepts and relationships. Currently, research focuses on the results or effects of computer simulations rather than on the enactment process of simulations in actual math teaching during co-design. Therefore, in this study, we aimed to identify the contradictions in the co-design process of a simulation-based math classroom as well as possible solutions to ameliorate them.

2. Literature Review

2.1 Computer Simulations for Math Teaching

Today, technology has become part of students' exploration of knowledge. Computer simulations, one of information and communications technology (ICT) applications, integrate learning areas including cognition, affect, and psychomotility as one and allows students to implement open-ended exploration and systematic experimentation (Ross & Bruce, 2012; Rutten et al., 2015). The specific characteristic of simulation represents complex real-world situations that can be changed by manipulating different parameters (Hillmayr et al., 2020). Through simulations, students could visualize their topics and interact with the technology in doing activities (Garcia, 2020).

Math is most widely known to be challenging for some K-12 students, especially the understanding of abstract concepts and mathematical relationships. Interactive simulation makes those sophisticated math concepts much easier to internalize for almost all students as they observe the direct consequences of the changes they make (Buckley et al., 2004). Most research focuses on the results or effects of computer simulations rather than on the process of teacher enactment of simulations in actual teaching. For example, Rutten et al. (2012) reviewed that numerous researchers have investigated the efficacy of computer simulations without measuring teacher influence or optimal instructional support.

Incorporating interactive digital tools into the math classroom requires the identification of innovative teaching and learning approaches that are suitable for such tools. This process involves identifying course components, making decisions regarding lesson structuring, sequencing, and pacing, as well as instructional strategies for monitoring and responding to student progress (Biggers et al., 2013; Remillard & Heck, 2014). Teachers' beliefs about the value of classroom teaching and the role of technology in the classroom significantly impact the enactment of these decisions and strategies. In cases that lack alignment, teachers may resist innovations or make substantial adaptations (Bates & Usiskin, 2016; Hermans et al., 2008). The collaborative design between teachers and researchers could be a promising way to facilitate the development of teachers' adaptive expertise and address theoretical as well as practical issues of teaching and learning (Ko et al., 2022). There are at least two key players who have influence in a teacher-researcher co-design community for the use of computer simulations in math teaching: teachers and educational researchers. In the co-design process, researchers provide educational principles and strategies to facilitate the innovation of teaching approaches and learning techniques. Teachers devise instructional activities to achieve the balance between pedagogical efficiency and innovative teaching practices (Goodyear & Casey, 2015).

2.2 Contradictions and Boundaries in Activity Systems

Teachers and researchers have been guided by their own cognitive paradigms and backgrounds for a long time, each pursuing distinct cognitions, understandings, and objectives in teaching. It is not surprising that certain contradictions may arise during mutual co-design, and the parties involved play a dynamic game in the contradiction (Goodyear & Casey, 2015). Cultural-History Activity Theory (CHAT) views human activity as inherently social and culturally embedded, emphasizing the interplay between individuals and their environment. From the perspective of CHAT, *contradictions* could be seen as historically accumulating structural tensions within and between activity systems (Ko et al., 2022). Collectives in the same activity system with a common goal orientation communicate, interact, and influence each other. Each activity system is composed of six core elements, including subject, object, community, mediating tools, rules, and division (Engeström, 2001). Based on CHAT framework, Qi et al. (2022) examined the contradictions and their plausible strategies between the mathematics teaching system and university research system, founding some typical contradictions such as tensions between school regulations and the object to promote teachers' professional development, as well as traditional teaching design versus research-informed teaching design.

The presence of contradictions is not always an obstacle to progress. Instead, they may trigger new attempts and changes by the subjects in the activity systems if identified and resolved properly (Yan & Yang, 2019). Potari et al. (2019) exposed the contradictions across teaching, research, and policy activity systems and their solutions, indicating identification and coordination as two main ways in the teaching and research activity to formulate a collectively meaningful object. In the middle of activity systems, the boundary represents the cultural difference and the potential difficulty of action and interaction across these systems but also represents the potential value of establishing communication and collaboration (Akkerman & Bakker, 2011). When collaborating across the boundaries of activity systems, teachers or researchers may need to enter into unfamiliar territory and combine ingredients from disparate sites to achieve hybrid situations (Engeström et al., 1995). This is commonly referred to as boundary crossing. It could prompt the subjects to question and critique existing practices or experiences, leading them to explore new solutions and ultimately generate innovation.

In our study, the CHAT and boundary crossing would be used to investigate the contradictions that emerge and the way to deal with them during a co-design process of a simulation-based math classroom across two key activity systems: teachers and educational researchers. Two research questions should be addressed:

RQ1: What were the emerging contradictions in the co-design process of a simulation-based math classroom?

RQ2: How did the participants deal with these contradictions between the teaching activity system and the research activity system?

3. Method

3.1 The systemic context and participants

Our co-design team was composed of two groups, including three researchers (one university professor, one teaching and research staff, and one graduate student) and five teachers (three in primary school and two principals). We use the acronyms R (researcher), T (teacher), or their combinations (RT) to refer to the activity systems to which participants belong. All the researchers had extensive research experience in educational technology, which could be seen as full members of the research activity system. These three researchers were represented by the abbreviations R1, R2, and R3, respectively. Teachers could be viewed as full members of the teaching activity system. They were all exposed to periodic teaching research activities with the eagerness to learn about new reform ideas to improve their teaching. Additionally, one of the principals had partial membership in the research activity system as he held a Master's degree in education and also played a key role in numerous educational research projects focused on classroom teaching supported by interactive simulations. This principal was represented by TR1, and the others were represented by T1, T2, T3, and T4.

The PhET is a site of research-based interactive computer simulation in teaching and learning physics, math, and other sciences (Garcia, 2020). Students engage in exploratory learning through the use of a simulator called 'Number Line: Integers' from PhET, which provides animated, interactive, and game-like environments. The whole team worked collaboratively for about two months (March 2023-April 2023) and prepared three versions of simulation-based mathematics instructional design for trial teaching in three different fifth-grade classes, 35 students in each. After each trial teaching, teachers and researchers attended a seminar meeting to reflect on and improve the current instructional design collaboratively.

3.2 Data collection and analysis

The collaboration took place through three post-lesson meetings (M1, M2, and M3) and numerous meetings in subgroups. After attending the final post-lesson meeting, the teacher who teaching this mathematics course with the support of PhET was invited to be interviewed. In the following, this interview was represented by the abbreviation I1. The interview questions include four main aspects: the process of using PhET simulation tool in a mathematics classroom; the experience of co-design and improving such a digital classroom; the perceptions of different opinions of teachers and researchers; the meaning of technology innovation and its relation to research or teaching. The data analyzed included the following: (1) video recordings of the three post-lesson meetings, (2) audio recordings of the interview, and (3) three versions of simulation-based mathematics instructional design.

To answer our first research question, the CHAT framework was used to identify and track the emerging contradictions between the teaching activity system and the research activity system in the co-design context. The contradictions were characterized by their content, the involved activity systems, and the elements of Engeström's (2001) interconnected triangles (see Figure 1).

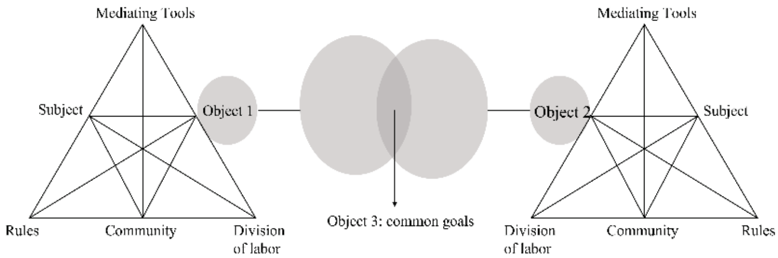

Figure 1. Interacting activity systems

To address the second research question, the construct of boundary crossing was used to examine how the management of the contradictions by the team members contributed to the design process. Akkerman and Bakker (2011) discerned and summarized four types of learning potential of boundary crossing: (a) Identification involves recognizing boundaries, acknowledging diverse perspectives, and bringing a renewed sense of different practices and related identities. (b) Coordination refers to cooperating efficiently in distributed work and dialogue between diverse partners to maintain the flow of work even in the absence of consensus. (c) Reflection involves recognizing and articulating distinctions between practices, thereby making explicit one's understanding and knowledge of a particular issue (perspective making), as well as looking at oneself through the perspectives of other worlds (perspective taking). (d) Transformation refers to the engagement of participants from diverse systems in constructive activities that result in significant changes to existing practices and even create novel cultural forms. People who cross boundaries serve as conduits for the introduction of elements from one practice into another, such as brokers and boundary crossers (Star & Griesemer, 1989). The identified contradictions indicated the boundary with the boundary brokers or objects. The process of dealing with this boundary was coded by such four types of learning at the boundaries.

4. Results

We structure the results based on the main contradictions that emerged while preparing and revising simulation-based mathematics instructional design. Three main contradictions were identified and coded, including theoretical ideas versus practical knowledge, simulation-based versus traditional teaching design, and generative interactions versus structured classroom culture. In each of the three subsequent subsections, we present through illustrative examples the identified contradictions, elements involved in activity systems, and how these contractions were managed through boundary crossing to jointly address research questions one and two.

4.1 Theoretical ideas versus practical knowledge

The first contradiction emerged in the co-design team's initial post-lesson meeting when they reflected on the implementation of a simulation-based math classroom utilizing PhET. Mathematics teachers made decisions in the teaching process and activities with their stereotypical thinking that relied on the content of mathematics textbooks. At this phase, conflicting perspectives between teaching and research activity systems emerged, indicating the gap between educational theories and practical knowledge. We provide example 1 to illustrate the elements of the activity systems involved in the contradiction and the process for dealing with it.

4.1.1 Example 1

In terms of teaching strategies, R1 suggested incorporating embodied cognition theory in the learning science field into the practical math classroom, and explained how to use, such as "hands-on or body movement", "changing the size and number of paces to reach a certain number on the number axis." One of the mathematics teachers T1 questioned the matching of embodied cognition theory with the content sequence of the textbook. T2 who taught this course expressed similar arguments:

> Physical activity is not the main focus of this lesson, right? In the first class, students need to know what the number axis is. And then in the second lesson, they should be able to look at numbers on it and describe where they are. Using body language representations would work better for these previous two lessons. But now, students need to compare the magnitude of numbers on the number axis. (T2, I1)

Contradiction: object and tools in research versus tools and rules in teaching
In example 1, it seems that the emerging contradiction is between the object (e.g., using educational theory to transform the mathematics classroom) and tools (e.g., embodied cognition theory) of research activity and the tools (e.g., mathematics textbook) and rules (e.g., organize teaching activities according to the sequence of mathematics textbook) of teacher communities. It appears to be prevalent that such contradiction emerges in the teacher-researcher co-design environment. Teachers often perceive researchers' solutions as too theoretical and insufficiently practical for implementation in real classrooms (Shrader et al., 2001). In contrast, researchers often view teachers' limited content knowledge as a hindrance to their effective contribution to co-design efforts (Roschelle et al., 2006). This contradiction reflects the distance between educational theory and pedagogical practice, and the new theory-oriented pedagogy has impacted teachers' instructional design according to established rules and textbook resources.

Boundary crossing remained in the process of identification
Dealing with the contradiction of "theoretical ideas versus practical knowledge" was a challenge for the co-design team. As a broker at the boundary, the researcher expressed the concept of embodied cognition in a language accessible to teachers and proposed concrete examples to apply this theoretical concept. Teachers were aware of the different perspectives of the researcher and the teacher insisted that the "physical activity" did not apply to teaching the knowledge of comparing the magnitude of numbers on the number axis. The boundary between the two activity systems explicitly signals an identification process demarcating the two communities' goals, tools, and rules.

4.2 Simulation-based versus traditional teaching design

This contradiction occurred during the first and third post-lesson meetings almost throughout the whole co-design process. The role of educational researchers was critical in formulating the common co-design goals, as researchers identified educational goals and provided PhET tools to achieve them based on their numerous similar research experiences. Teachers have hardly ever experimented with new educational resources in the classroom before, bringing many obstacles to the introduction of simulation resources. We provide two examples to illustrate divergent views about the balance between simulation-based teaching design and traditional teaching design, as well as the discussions for managing them.

4.2.1 Example 2

The goal proposed by researchers was to use simulation technology to drive innovation in classroom teaching. T2 expressed his confusion about how to achieve it, “We are using PhET software for the first time and have no clue how to use it to help me teach math.” T2 further pointed out that the software was not effective for the first trial teaching, “The software was used less in math classes and did not show its benefits.” After the first post-lesson meeting, TR1 provided T2 with several excellent exemplary lessons integrating PhET resources.

Members of the research group, responding to T2’s concerns, clarified that an inquiry-based teaching approach not only facilitates software functionality but also enhances student motivation:

> The teacher does not need to give a concrete hypothesis and ask the students to verify this hypothesis. Instead, students can assume which is greater between a positive number and a negative number by themselves, and get some findings by operating on PhET software. (R1, M2)

T2 mentioned in the interview that advice from researchers and other senior teachers had been instrumental in moving him out of the limitations of traditional instructional design:

> After the first trial, several teachers, TR1, and R1 suggested that the students should make full use of the software’s features to explore mathematical rules. I redesigned the inquiry process of students in more detail. For example, I will demonstrate to students how to use this software to explore, and students will learn the teacher's manipulations to explore the rules of comparing the size of positive and negative numbers and summarize the method of comparing the size. (T2, I1)

4.2.2 Example 3

Teachers, who had higher original expectations for its functionality, were not satisfied with the features currently provided by the simulation resource, such as “the position of the input number cannot be presented on the number axis”. Besides, T2, T3, and T4 expressed their desire for the PhET software to add the function of comparing the magnitude of negative fractions:

> Comparing the size of negative fractions is difficult for students. It would be better if the fraction could be represented on this software. Then we can use image examples to help students break through the difficult knowledge point of comparing the size of negative fractions. (T2, M3)

TR1 explained that this is due to the existence of diverse teaching orientations and requirements among different countries, “We started from the Chinese math teaching methods and textbooks, perhaps this software is mainly for game-based learning in other countries”. R1 pointed out that “I will write down the problems we have and try to send an email to the PhET operations team with our suggestions for program improvements.”

In T2’s interview, he reflected on the reciprocal relationship between technology and teaching:

> I think that no matter what technology is used, it is ultimately for teaching, and these technologies are designed to help us teach better. The problems we find in the teaching process can sometimes, in turn, drive the development of these technologies. For example, if it can follow the teaching in the improvement, it may become more and more perfect, making it even more suitable for most school teachers to use. (T2, I1)

Contradiction: object and tools in research versus tools in teaching
Interpreting T2's position, a contradiction could be recognized which is between the object (e.g., technology integration into classroom practice) and tools (e.g., PhET simulation tool) of the research activity system and the tools in the teaching activity system (e.g., the content of mathematics textbooks, traditional teaching approaches). The introduction of advanced technology undoubtedly presented challenges for current teaching practices, as teachers were unfamiliar with its implementation and efficacy (Qi et al., 2022). When teachers feel uncomfortable or unprepared, their ability to instruct with simulations may be diminished (Stern et al., 2008). This contradiction reflects the division between new digital technologies and traditional instructional design. It is not enough for researchers to simply make resources available to teachers. What is more important is to teach teachers how to use these in the classroom to maximize the effect of technology.

Boundary crossing was maintained in perspective making and taking
In dealing with the contradiction, R1 and TR1 act as brokers between research and teaching offering ideas and explanations for teachers to overcome cognitive limitations. R1 introduced the student-centered discovery approach, and TR1 gave teachers excellent examples of lessons that integrate PhET resources, including classroom videos and teaching design. From initial confusion and skepticism about the use of simulation resources in the classroom, the teacher rethought his teaching practices through an educational research lens, incorporating a learner-centered inquiry-based teaching approach and adopting critical perspectives towards technology's role. This indicates boundary crossing in terms of perspective making and taking. Consistent with existing studies, technology could promote teachers' pedagogical design capacity and help them design innovative instructional practices to better support student investigations (Beyer & Davis, 2012; Davis et al., 2016). Meanwhile, teachers' beliefs regarding the role of technology in the classroom are pivotal in shaping their instructional decisions or actions (Bates & Usiskin, 2016; Hermans et al., 2008; Webb et al., 2015).

4.3 Generative interactions versus structured classroom culture

The contradiction between generative interactions and structured classroom culture emerged in the subsequent stages of co-design activities (second post-lesson meeting and third post-lesson meeting). The academic researchers in the team were more focused on generative interactions between teachers and students from the perspective of learning analysis. The emerging contradiction here concerns whether generative discourses were too far from the teaching style and structured classroom culture cultivated over time. The analysis of example 4 illustrates certain elements between teaching and research activity systems involved in contradiction and the process of ameliorating it.

4.3.1 Example 4

R2 pointed out that T2 should capture students' generative expressions and guide them toward deeper elaboration and expression:

> The resources generated are abundant, but there is one place T2 needs to grab. A student answered that the number is infinite, and T2 couldn't just sit her down. It should be a little more open in the dialogue between teacher and student, such as a further question that allows students to elaborate and express their ideas in depth. (R2, M3)

In contrast, T2 responded to the above-mentioned issues in the interview by arguing that these generative conversations were not entirely applicable to teaching his class:

> If they don't know students in my class, their suggestions may not be too in line with the actual situation. I just accept part of it. The students in Ms. Chen's class are very open and outspoken when answering questions, while the students in my class are

> more timid and less outspoken. This is because my usual training requires students to strictly answer questions according to my requirements and rarely think outside the box. (T2, I1)

In the later discussion, T2 reflected that generative interactions have an important role in developing students' divergent thinking. He realized that the current didactic class culture should be changed, “We should make students dare to communicate and think more divergently because students are the center of learning.” Teachers should fully anticipate "how students might react in class".

Contradiction: object and rules in research versus rules in teaching
In terms of the elements of the CHAT triangle, the goals (e.g., adequate student-teacher generative interaction in the classroom) and rules (e.g., research norms) of the research activity contradict the rules of the teaching activity (e.g., established classroom rules, structured culture). As Reiser et al. (2000) noted, teachers and researchers involved in co-design always follow inconsistent workplace norms which bring challenges. Teachers' focus was on the feasibility of implementation and the matching degree to student characteristics. However, researchers tended to adopt an analytic perspective to focus on goals first. This contradiction reflects the uniqueness of cultural norms in teaching and research, as well as the boundaries between generative interactions and existing classroom cultures.

Boundary crossing was in the process of perspective making and taking
In dealing with this contradiction, R2 seems to play the role of boundary people providing practical ideas and strategies (e.g., guiding questions) for T2 to change from structured classroom management forms and teaching paradigms. From the interview data, T2 renewed insight into the importance of generative interactions for developing students' divergent thinking. Also, he demonstrated his willingness to change his classroom culture to make it more divergent and open to generative interactions. This displays the boundary crossing in terms of perspective making and taking.

5. Discussion and conclusion

In our study, contradictions emerged in teaching and research activity systems through simulation-based math classroom co-design, and their boundary crossings were explicated. The object, tools, and rules of the research activity appeared to contradict mainly the elements of tools and rules in the teaching activity. The object of the research activity is to transform the classroom with simulation resources to promote inquiry-based learning and understanding of mathematical relationships. The teaching reality and classroom culture posed the researchers with a dilemma in terms of how to communicate clearly with teachers about their implementation of the research-oriented teaching strategies and simulation resources in daily teaching.

Contrary to the results of previous studies, boundary crossing mainly involves constructing a new system that takes different perspectives into account rather than simply questioning (Potari et al., 2019). This is partly due to the strong and rich research base of the researcher group. Teachers trusted the expertise of their co-design colleagues, who acted as brokers to bring plentiful resources (PhET simulation tool, educational theories, principals, strategies, and even examples of course design). When teachers understood and formulated a shared meaningful object with the support of researchers, their developing beliefs about instructional orientation and the value of technology can drive changes in teaching decisions and behaviors that lead to a smooth process of boundary crossing (Webb et al., 2015).

When contradictions emerged, the elements of activity systems (Engeström, 2001) could be used to understand the sources of these contradictions and their boundaries. From the perspective of boundary crossing, we depict the process of overcoming contradictions in the interactions between teaching and research activity systems. Incorporating CHAT and boundary crossing, our analysis highlights the dynamic process of simulation-based classroom co-design by culturally diverse groups, in which contradictions inevitably arise. However, the dissolution of contradictions contributes to the establishment of more harmonious collaborative relationships that serve as a driving force for the co-design community. This detailed analysis also depicts how teachers iteratively change their pedagogical conceptions and actions to learn and develop. Based on these findings, we will provide further support for teachers to optimize the learning opportunities offered by the collaborative design and enable them to implement a simulation-based digital math classroom independently.

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