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Boundary interaction: Towards developing a mobile technology-enabled science curriculum to integrate learning in the informal spaces

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Abstract

This paper explores the crossover between formal learning and learning in informal spaces supported by mobile technology, and proposes design principles for educators to carry out a science curriculum, namely Boundary Activity-based Science Curriculum (BAbSC). The conceptualization of the boundary object, and the principles of boundary activity as the key elements to fuse the merits of learning in informal spaces with formal learning, are discussed and elaborated. The key elements of BAbSC are further articulated to provide the framework for curriculum design and development from a holistic perspective. The proposed principles and framework will reinforce the theoretical underpinnings of mobile technology-enabled curriculum design and development, and can be used to guide teachers to implement curriculum in a more principle-based and structured manner.

Introduction

Research has showed that students' authentic experiences outside of the classroom might have a major impact on their science learning because these experiences provide opportunities for students to construct, modify and reflect on the content knowledge they gain in the classroom (Tran, 2011). Recognizing the merits of learning in informal spaces, educators endorse the use of outside resources to support science learning and emphasize the need of integrating learning in informal spaces with formal learning. However, challenges were encountered. The major challenges in this area are: learning in informal spaces is usually positioned as supplementary to formal learning, thus such activities are commonly designed as sporadic and ephemeral visits, with a dearth of follow-up activities. There is also a lack of principles or frameworks for guiding a curriculum that connects the formal and informal spaces. When conducting such learning activities, teachers do not establish clear and specific objectives for students' learning in informal spaces. This often results in little monitoring of the learning process and few opportunities offered for students to elaborate on and deepen learning in the classroom. Furthermore, the depth of investigation on learning in informal spaces is much less than that of research efforts on formal learning. Relevant studies are generally reported as cases of "best practices" with little discussion on the pedagogy and principles of learning in informal contexts. Thus, we know little about how these experiences can best be integrated into the school curriculum. Although the emergence of

Practitioner Notes

What is already known about this topic

- The ubiquitous use of mobile technology creates various opportunities for connecting the formal learning process with learning in informal spaces.
- There needs to be a deeper understanding of the principles for guiding the design of a curriculum that connects the learning in formal with the learning in informal spaces.
- Although the emergence of mobile learning, seamless learning, interactive learning and the like leverages technology in teaching and learning of out-of-classroom activities, there are few representative mobile technology-enabled curricula.

What this paper adds

- Boundary activity is defined and described in the domain of technology-supported teaching and learning, which is rarely discussed in this field.
- The conceptualization of the boundary object and boundary activity tightens the linkage of learning between formal and informal spaces.
- The principles of BAbSC, which fully consider the instructional elements and how they can be systemically incorporated into school curriculum, will serve as a guide for instructional design of a mobile technology-enabled curriculum in a holistic way.
- The proposal of the design principles for BAbSC will remedy the weaknesses of the pedagogical design and development of the technology-enabled curriculum.

Implications for practice and/or policy

- The integration of formal learning with the learning in informal spaces could maximize the merits of mobile technology for science learning.
- With the conceptualization of the boundary activity, the mobile technology-enabled teaching and learning will be guided and implemented in a more practical and structured way.
- The design principles of BAbSC will inform the design and development of learning in informal spaces and yet is relevant within the ambit of the formal education system.

mobile learning, seamless learning, interactive learning and the like, leverages technology (ie, mobile technology) in learning activities outside of the classroom, there is no representative curriculum that addresses the best practices in this arena.

The above issues motivate the proposed design principles of a mobile technology-enabled science curriculum, namely, Boundary Activity-based Science Curriculum (BAbSC in short). The paper takes a holistic view of boundary activity in the domain of technology-supported teaching and learning, for the purpose of connecting learning between formal and informal spaces. Learning activities in the informal spaces of BAbSC constitute an integral rather than a supplementary part. The proposed curriculum has the potential of changing teachers and students' perspectives of learning in the informal spaces, and of guiding science education across formal spaces and informal spaces in a structured and principle-based manner supported by technology. In the paper, the principles of BAbSC will be articulated in terms of the concept of boundary object, the design principles of a boundary activity, and the elements of BAbSC. A lesson exemplar will be showcased for better understanding on how boundary activities look like in the standard science curriculum in the Hong Kong primary school level. This will provide the guidelines for the instructional design of mobile technology-supported curriculum focusing on better integrating formal and informal learning contexts, as well as more practical ways for the teachers to conduct the outdoor activities.

Literature

The value of science learning in informal spaces

In science, the most popular way for students to engage in informal learning spaces include communicating, exploring and understanding science in museums, science centers, botanical gardens, zoos, field centers, etc. However, it is only in recent decades that learning in informal spaces has received recognition for its value to formal education (Black, 2005). Studies show that the more students are exposed to informal contexts, the more they would gain (Gerber, Cavallo, & Marek, 2001). The greater use of the out-of-school science learning would make school science education more effective and motivating (Braund & Reiss, 2006). Thus, the Next Generation Science Standards (2013) calls for a deeper understanding and application of content to develop high levels of cognition in students through the practice of science.

Hofstein and Rosenfeld (1996) believe that future research in science education should focus on how to effectively blend informal and formal learning experiences in order to significantly enhance science learning. Bell, Lewenstein, Shouse, and Feder (2009) share the same viewpoint that informal learning contexts should be seen as complementary to formal schooling rather than competing with it. They propose a greater coherence of informal environments and K-12 classrooms. Behrendt and Franklin (2014) emphasize the necessity of involving the pedagogies or principles of learning in informal spaces in teacher education. They suggest that teacher education programs should include experiential education and field trip preparation, and implementation for all pre-service teachers so as to help them understand the necessity of pre-planning, participation and student reflection. In current teacher training programs, this area has been somewhat neglected.

Mobile technology mediating formal learning and learning in informal spaces

There is much potential in mobile learning to motivate student interest, enhance student memory and foster students' critical thinking, collaboration and creativity (Otero, Milrad, Santos, Verssimo, & Torres, 2011; Terras & Ramsay, 2012). Recently, mobile technologies, together with the appropriate pedagogies, have been gaining popularity as a tool for facilitating students' learning in informal spaces. Rogers and Price (2008) incorporated the use of mobile tools in students' field trips guided by the collaborative inquiry principle. Their results showed that the tools helped students engaged more in discussion, interpretation, sharing and reflection. Song, Wong, and Looi (2012) proposed a goal-based approach to designing a mobile curriculum. The approach was effective in developing students' scientific knowledge and self-directed learning skills. Ahmed and Parsons (2013) developed a mobile system called ThinknLearn for supporting students' abductive science inquiry. The findings indicated that students enhanced their skills on generating hypotheses and critical thinking.

As Sharples, Sánchez, Milrad, and Vavoula (2009) noted, an instructional design theory for mobile learning has not been fully articulated. In reviewing the published reports, while most were about creating a learning environment for leveraging the affordances of mobile technologies, the learning experiences they supported were short-term and practice-oriented, and without an explication of their theoretical underpinnings (Sun, Looi, & Wu, 2016). Moreover, few researchers have worked on conceptualizing sustainable learning with mobile technologies via immersion into the standard science curriculum with appropriate pedagogical principles and instructional design.

Principles of boundary activity

Boundary activity: the knot connecting formal learning and learning in informal spaces

Prior to explicitly delivering the meaning of boundary activity, there is another term to introduce: boundary object, a term which has been discussed in science education. Boundary object refers to the common idea generated in scientific work which needs cooperation with among divergent viewpoints and the need for generalizable findings (Star & Griesemer, 1989). It can be either abstract or material, for example, field notes, specimens and artifacts which can be the connections between formal learning and learning in the informal spaces. In a more elaborated definition from Wenger's study (Wenger, 1998), boundary object is one type of the connections between communities of practices, namely, artifacts, documents, terms, concepts and other forms of reification and around which communities of practices can organized their interconnections. In brief, boundary object can be an abstract concept introduced in the classroom and elaborated outside of the classroom, or a guiding question related to a key concept. It can be an event or a science phenomenon which requires students to investigate outside of class and discuss in class. The boundary object can also be a physical object which is generated in or outside of the classroom. In sum, as a metaphor, boundary object is the physical or abstract objects generated by the interaction between boundary of formal and informal spaces, which may play an important role in students' science learning in various contexts, especially for the outsides activities. Once integrated with the use of mobile technology, there will be more representations of boundary objects, for example, concept maps, drawings, photos, videos, notes, etc.

We propose the concept of "boundary activity," building on an idea that has been implicitly discussed in relevant studies. Kisiel (2014) proposes that joining resources from both formal and informal learning settings is an effective strategy that enhances students' interest in science learning. He coined a term "boundary activity" to define the activities which connect schools and informal science institutions. It refers to "those encounters between schools and informal science spaces that involve some kind of designed program-field trip, outreach, and teacher workshop with specific educational objectives." Therefore, boundary activity is a deeper, practice-based interaction which has the potential to better facilitate interaction between the two communities. Based on the above ideas, we define boundary activity as the learning activities which take place in either formal or informal contexts, and contain at least one boundary object that bridge learning in formal and informal environments.

Our literature review provides some case studies which suggested the use of boundary objects for conducting boundary activities. In Gilbert and Priest's (1997) study, to link the learning experience in museum visits with the science topics learned in class, student group activities were focused on discussing the "critical incidents" during the visits. In this case, "critical incidents" were the boundary object generated in the museum visits. Tsurusaki, Calabrese Barton, Tan, Koch, and Contento (2012) created "transformative boundary objects" and explored how the transformative boundary objects work in the teaching practices of a teacher with the aim of engaging students in science learning. Three types of boundary objects were discussed: bar graph, research questions and nutrition in the teaching of healthful food. Building on these researches, we intend to deepen the conception of boundary activities in the domain of mobile learning. We would like to see how these boundary activities work in diverse learning contexts and improve the interaction of the in-classroom and out-of-classroom practices.

The components of boundary activity

Research has shown that if field activities are "properly conceived, adequately planned, well taught and effectively followed up," they can offer "learners the opportunities to develop their knowledge and skills in ways that add value to their everyday experiences in the classroom" (Patrick *et al.*, 2013; Rickinson *et al.*, 2004). Sharples *et al.* (2014) proposed employing scripted

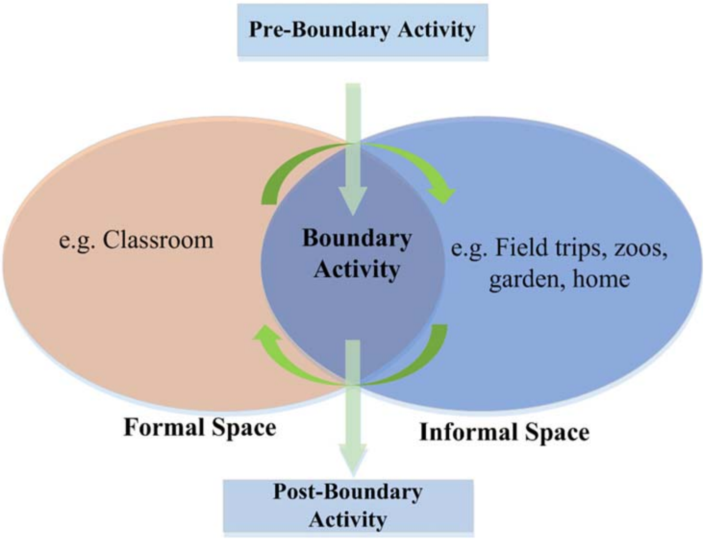

Figure 1: The boundary interaction between learning in formal and informal spaces [Colour figure can be viewed at wileyonlinelibrary.com]

learning methods to conduct outside inquiry activities, in which the teacher initiates a structured activity with the use of mobile devices inside the classroom, and then continues with it outdoors. DeWitt and Osborne (2007) proposed the key elements of learning design principles in informal contexts which inform the boundary activity design such that the boundary activities can be located either in the formal spaces or informal spaces. It should fit into appropriate pedagogical principles across formal learning and learning in informal spaces, and serve to attain the same learning objectives.

Here, we propose three components of a boundary activity: boundary object, structure and learning objectives. We refine the idea to delineate between boundary object, activity structure and learning objectives: (1) The boundary object is a prerequisite for designing the boundary activities. It acts as a knot which serves to bridge learning in and out of the classroom and capture the learning process in the informal spaces in particular. With boundary objects, the boundary activities will better fit into the standard curriculum. (2) Structure: the boundary activity is conducted in the pre-, during- and post-activity pattern to guarantee the continuum and stability of cognition or skills developed across the learning contexts. (3) Learning objective: the learning objectives of boundary activity should be defined based on the curriculum standard and the characteristics of the contextual variables in practice. These three components are proposed to guide the design and implementation of a BAbSC. Figure 1 represents the structure of boundary activity and the interaction between formal learning and learning in informal spaces. The boundary activity is conducted across the formal space and informal spaces. It is usually prepared and instructed in the formal learning context (ie, classroom) prior to carrying out it. With mobile devices, data, evidence and any responses related to the tasks of boundary activities generated in informal spaces can be the representative boundary objects, prompting the boundary interactions taking place.

Boundary activity-based science curriculum (BAbSC)

The elements of BAbSC

Theories of curriculum development have been consulted to define and refine the key elements of BAbSC. Thijs and van den Akker conclude that there are 10 components of the curriculum:

rationale or vision, aims and objectives, content, learning activities, teacher role, materials and resources, grouping, location, time and assessment. For more details, please refer to Thijs & van den Akker (2009). The components guide the generation of BAbSC elements (Table 1). In BAbSC, the instruction of the content knowledge is guided by the pedagogical principles of collaborative inquiry, seamless learning and mobile learning (Wong & Looi, 2011). Mobile devices incorporating inquiry learning tools are used as the mediated tools in and out of the classroom. Two mainstream web-based inquiry learning platforms: Web-based Inquiry Science Environment (WISE) and nQuire-it, are proposed to be adopted. The boundary activities will include the mobile and non-mobile learning activities which utilize the boundary objects to facilitate learning in and out of the classroom. The structured boundary activities will be designed and implemented before, during and after class. Students will receive diversified opportunities to investigate scientific phenomena in virtual labs and authentic contexts. During students' inquiry, the teacher will play an important role in implementing the boundary activities for coordinating students' learning in the classroom and out of the classroom with the aims of developing students' understanding and relevant skills.

The medium for running boundary activities in BAbSC: nQuire-it and WISE

In implementing BAbSC, we envisage the use of a stable and multifunctional system to support students in-classroom activities and out-of-classroom activities, and capture interactions of students and their teacher in the various contexts (ie, online & authentic learning, in classroom & out of classroom). Two web-based platforms will be integrated in BAbSC: nQuire-it (http://www.nquire-it.org) which facilitates students' inquiry activities in informal spaces, and WISE (https://wise.berkeley.edu/) which guides students' online inquiry in a step-by-step manner. Figure 2 represents the overall picture of the roles nQuire-it and WISE play in BAbSC. In comparison of other sensor-based technologies, nQuire-it is a learning platform which is more suitable for conducting outside activities in either guided inquiry or open inquiry, and either in an individual or collaborative way (Llewellyn, 2007; Wenning, 2005). Specifically, it supports students to collect real-time data outside (ie, real experimentation, hands-on activities, home activities, field trips, etc) using Spot-it (a mobile tool for capturing images and annotating things with notes) and Sense-it (a sensor-based mobile tool for collecting and sharing data using phone sensors: accelerometer, gyroscope, light and sound, etc). Thus, the use of nQuire-it will particularly enhance students' interaction with the informal learning spaces for testing their hypotheses and deepening understanding through authentic learning activities. In this case, the real-time data in the form of photos of scientific phenomena and graphs are the major boundary objects. The activities for planning, conducting data collection and sharing are the boundary activities. As a learning management system (LMS), WISE provides teachers with a powerful authoring tool to design guided inquiry-based activities. With the use of WISE, the learning taking place in formal spaces and informal spaces can be merged into this system. A WISE lesson facilitates students' online investigation of simulation, videos and virtual labs in and out of the classroom (Slotta & Linn, 2009). The WISE system provides various learning tools, such as a drawing tool, concept map tool, simulations, peer discussion tool and others to support student learning and communication in and out of the classroom. As a result, students receive more opportunities to investigate in the virtual contexts and report their findings online. More importantly, teacher-student and student-student interaction, students' responses, teacher feedback and assessment can be traced and recorded as evidence of students' performance in BAbSC. nQuire-it can be flexibly inserted into the learning design of WISE lessons. In this Hong Kong-based study, the synergic use of nQuire-it and WISE enables students to investigate both the virtual and authentic scientific phenomena and to interact with their teachers and classmates any time anywhere.

Table 1: Key elements of the BAbSC

Key elements	*Content*	*Rationale*
Pedagogical principles	Guided or open inquiry principles: • Guided inquiry activities are designed for classroom learning • Open inquiry activities are designed for outside learning • Seamless learning • Mobile learning • Collaborative learning	Transforming the traditional inquiry-based classroom into more open, learner-centered classroom; facilitating students' authentic inquiry through interacting with various authentic contexts; maximizing the value of mobile learning through incorporating different levels of inquiry activities; developing students' collaborative learning skills through solving problems together.
Content	• Science curriculum (ie, Hong Kong Secondary Science Curriculum)	The design of the boundary activities will follow the requirements of the science syllabus and the learning objectives.
Learning objectives	• Knowledge understanding • Application of skills and processes • Ethics and attitudes	
Resources	• Science textbooks • Learning tools: WISE, nQuire-it • Out-of-classroom resources • Device: tablets, mobile phones	
Activities	• Boundary activities: mobile technology acts as the major tools. • Non-boundary activities	Leverage the affordances of mobile technologies for linking formal learning and learning in informal spaces, and support the consolidation of student understanding in informal spaces.
Location/time	• Classroom—class time • Out of classroom—out of class time	Improve students' inquiry skills through authentic inquiry out of class time.
Teacher's role	• Flexible roles in and out of the classroom	Develop teacher competency on implementing the boundary activities.
Student's role	• Active learners	Develop students' self-directed learning and collaborative learning skills through personal inquiry.
Technology's role	• Integrated flexibly into and with the content and activities: • Presentation tools • Learning tools (eg, concept map tool, reflective tool, drawing tool, data collecting tool, assessment tool)	Maximize the value of technology for enriching science learning through well-designed learning activities.
Assessment	• Formative assessment • Mobile learning artefacts • Activity performance • Summative assessment • Inquiry skills tests • Academic tests	Develop teacher competency on formative assessment of science inquiry and collaborative learning.

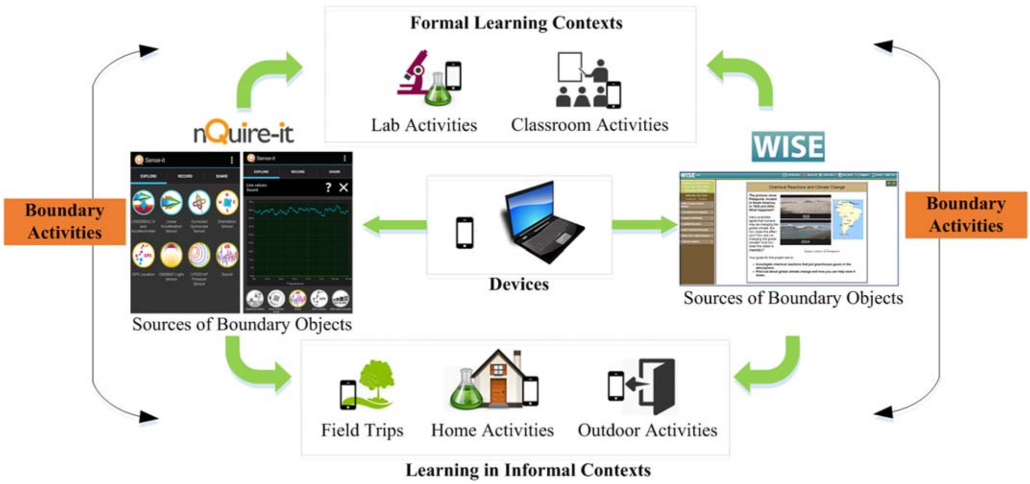

Figure 2: Harnessing WISE and nQuire-it in designing boundary activities [Colour figure can be viewed at wileyonlinelibrary.com]

Lesson exemplar of BAbSC

Table 2 shows a lesson exemplar of BAbSC. The topic is Motion and Force, from the Hong Kong primary science (Primary 6). In the lesson, four inquiry phases consisting of Questioning and Context, Spot-It Exploration, Sharing and discussion, Summary and Reflection are organized by the WISE system and the nQuire-it platform. It facilitates students' inquiry learning in an explicit manner. In the pre-boundary activity stage, students are provided with instructions of tasks and guiding questions. During the boundary activities, students are engaged in a series of hands-on activities with mobile devices: collecting data, uploading data, reviewing data and doing peer assessment. In post-boundary activities, students' work is further discussed and assessed in class. Finally, they consolidate their understanding and respond to the guided questions in WISE system. Through these kinds of activities, the teacher will have a clearer picture of how a boundary activity should be conducted, and what are the boundary objects (ie, guiding questions, spot-it learning artefacts), as well the purposes of the post boundary activities (ie, requiring doing higher cognitive levels of activities).

Conclusions and implications

While it may be impractical to define precisely what formal or informal learning is, instructors are now more than ever trying to understand the affordances of each to create effective learning designs (Czerkawski, 2016). Our intention is not to distinguish them or to endorse one of them, but to utilize and synergize them for supporting more powerful students' learning. Although there have been relevant principles of learning design in the field of the technology-supported learning, more potential exists for investigating in-depth on the why, what and how of the interactions between formal learning and learning in informal spaces facilitated by technology. In this paper, we propose the conception of boundary object in the field of technology-supported teaching and learning. The boundary object serves as a medium for promoting the effective learning interactions between formal and informal learning spaces. The meaningful interactions which are frequently discussed in the relevant studies have been considered as the most important component of any learning environment (Woo & Reeves, 2007). Particularly, the boundary interaction of learning between formal and informal spaces has been discussed in science education but more investigation is needed. Meaningful and effective learning facilitated by mobile technology will

Table 2: A lesson exemplar of BAbSC

Inquiry phase	*Content*	*Learning spaces*	*Boundary activities*
1. Questioning and context (WISE)	Have you noticed the science phenomena related to friction force? Could you take the photos of these phenomena? And think about the following questions: 1. What is the role played by the friction force in these science phenomena? 2. Does the friction force play an active role or a negative role? 3. If negative, how do you decrease it or prevent it?	Classroom: Teacher assigns tasks and introduces the tasks with details in the classroom.	Pre-boundary activity
2. Spot-it exploration (nQuire-it platform)	Using Spot-It to upload the photos of friction force in daily life and share the evidence with classmates. The students are also required to comment on each other's work.	Outside and home: Students take photos outsides and upload the photos via Spot-it and review their classmates' work and comment their work and at home.	Boundary activities
3. Sharing and discussion (WISE and nQuire-it platform)	The teacher presents all students' work uploaded in nQuire-it platform, and identifies the quality of work and discusses with the students.	Classroom: Discussion and interaction focus on the boundary objects in classroom.	Post-boundary activities
4. Summary and reflection (WISE)	The students summarize the science phenomena of friction force by responding to the three guiding questions.	Classroom or home: The summary and reflection enable students to elaborate on their understanding of friction force.	Post-boundary activities

have much potential to be generated by student-student interactions, student-context interactions and student-teacher interactions in these two learning contexts. These interactions may be difficult to observe without the creation of boundary objects. Further, the identification of the structure of a boundary activity highlights the positive learning behaviors in the different stages and serves as an organization of learning activities in and out of classroom. For mobile learning activities, especially for the out-of-classroom activities, pre-activities and post-activities need to be designed for drawing out the students' prior knowledge, for fostering dialogic interactions, and for consolidating activity findings. Peer-discussion and self-reflection will be the major patterns of the post activities for students' deep understanding of the relevant scientific concepts learnt in the classroom as showcased in the above lesson exemplar. Boundary activities which link learning in and out of the classroom, in formal and informal contexts can be rigorously designed and implemented to maximize students' learning.

Relevant studies have demonstrated that the affordances of mobile technologies can support learning taking place in informal contexts (Looi *et al*., 2014; Sharples *et al*., 2014; Song *et al*. 2012). They can record and provide a window into the students' science learning processes taking place in and across contexts. Thus we propose to integrate the use of inquiry-based LMS in WISE with the mobile sensor-based platform of nQuire-it. We hope the articulation of conceptions of boundary objects, boundary activities and boundary activity-based curriculum enabled by technology would further contribute to the theoretical basis of the design of mobile learning. Meanwhile, the principles of designing and conducting boundary activities could guide the teachers to implement mobile learning in and out of classroom in practical ways. The proposal of boundary activities which bridge formal and informal learning spaces will help the teachers to recognize the role played by the informal spaces for students' science learning as an integral and essential part of the standard curriculum.

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Statements on open data, ethics and conflict of interest
The relevant data sets collected during this research will be made openly available through the Education University of Hong Kong online repository.

This project was approved by the Education University of Hong Kong ethics committee, prior to the commencement of the collection of data.

There are no conflicts of interest involving either of the authors of this paper.

References
Ahmed, S., & Parsons, D. (2013). Abductive science inquiry using mobile devices in the classroom. *Computers & Education*, *63*, 62–72.
Behrendt, M., & Franklin, T. (2014). A review of research on school field trips and their value in education. *International Journal of Environmental & Science Education*, *9*(3), 235–245.
Bell, P., Lewenstein, B., Shouse, A. W., & Feder, M. A. (2009). *Learning science in informal environments: People, places, and pursuits*. Washington, DC: The National Academy of Sciences.
Black, G. (2005). *The engaging museum*. London: Routledge.
Braund, M., & Reiss, M (2006). Towards a more authentic science curriculum: The contribution of out-of-school learning. *International Journal of Science Education*, *28*(12), 1373–1388.
Czerkawski, B. C. (2016). Blending formal and informal learning networks for online learning. *International Review of Research in Open and Distributed Learning*, *17*(3), 138–156. Retrieved 7 May 2016, from http://www.irrodl.org/index.php/irrodl/article/view/2344/3689
DeWitt, J., & Osborne, J. (2007). Supporting teachers on science focused school trips: Towards an integrated framework of theory and practice. *International Journal of Science Education*, *29*(6), 685–710.
Gerber, B. L., Cavallo, A. M., & Marek, E. A. (2001). Relationships among informal learning environments, teaching procedures and scientific reasoning ability. *International Journal of Science Education*, *23*(5), 535–549.
Gilbert, J., & Priest, M. (1997). Models and discourse: A primary school science class visit to a museum. *Science Education*, *81*(6), 749–762.
Hofstein, A., & Rosenfeld, S. (1996). Bridging the gap between formal and informal science learning. *Studies in Science Education*, *28*(1), 87–112.
Kisiel, J. F. (2014). Clarifying the complexities of school–museum interactions: Perspectives from two communities. *Journal of Research in Science Teaching*, *51*(3), 342–367.

Llewellyn, D. (2007). *Inquire within: implementing inquiry-based science standards in grades 3-8*. Thousand Oaks, CA: Corwin.

Looi, C.-K, Sun, D., Wu, L. K., Seow, P., Chia, G., Wong, L-H., . . . Norris, C. (2014). Implementing mobile learning curricula in a grade level: Empirical study of learning effectiveness at scale. *Computers & Education*, *77*, 101–115.

National Academy of Sciences (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press.

Otero, N., Milrad, M., Santos, A. J., Verssimo, M., & Torres, N. (2011). Challenges in designing seamless-learning scenarios: Affective and emotional effects on external representations. *International Journal of Mobile Learning and Organisation*, 5(1), 15–27.

Rickinson, M., Dillon, J., Teamey, K., Morris, M., Choi, M. Y., Sanders, D., & Benefield, P. (2004). *A review of research on outdoor learning*. Shrewsbury: National Foundation for Educational Research and King's College London.

Rogers, Y., & Price, S. (2008). The role of mobile devices in facilitating collaborative inquiry *in situ*. *Research and Practice in Technology Enhanced Learning*, *3*(3), 209–229.

Sharples, M., Scanlon, E., Ainsworth, S., Anastopoulou, S., Collins, T., Crook, C., . . . O'Malley, C. (2014). Personal inquiry: Orchestrating science investigations within and beyond the classroom. *Journal of the Learning Sciences*, *24*, 308–341. doi: 10.1080/10508406.2014.944642.

Sharples, M., Sánchez, I. A., Milrad, M., & Vavoula, G. (2009). Mobile learning: Small devices, big issues. In: N. Balacheff, S. Ludvigsen, T. de Jong, & S. Barnes (Eds.), *Technology enhanced learning: Principles and products* (pp. 233–249). Heidelberg, Germany: Springer.

Song, Y., Wong, L.-H., & Looi, C.-K. (2012). Fostering personalized learning in science inquiry supported by mobile technologies. *Education Technology Research Development*, *60*(4), 679–701.

Star, S. L., & Griesemer, J. R.(1989). Institutional ecology, translation and boundary objects: Amateurs and professionals in Berkeley's museum of vertebrate zoology, 1907-39. *Social Studies of Science*, *19*(3), 387–420.

Sun, D., Looi, C.-K., & Wu, L. (2016). The innovative immersion of mobile learning into a science curriculum in Singapore: An exploratory study. *Research in Science Education*, *46*, 547. doi:10.1007/s11165-015-9471-0

Terras, M. M., & Ramsay, J. (2012). The five central psychological challenges facing effective mobile learning. *British Journal of Educational Technology*, *43*(5), 820–832.

Thijs, A., & van den Akker, J. (Eds.). (2009). *Curriculum in development*. Enschede, Netherlands: SLO–Netherlands Institute for Curriculum Development. Retrieved 7 May 2016, from http://www.slo.nl/downloads/2009/curriculum-in-development.pdf/

Tran, N. M. (2011). The relationship between students' connections to out-of-school experiences and factors associated with science learning. *International Journal of Science Education*, *33*(12), 1625–1651.

Tsurusaki, B. K., Calabrese Barton, A., Tan, E., Koch, P., & Contento, I. (2012). Using transformative boundary objects to create critical engagement in science: A case study. *Science Education*, *97*(1), 1–31.

Wenger, E. (1998) *Communities of practice: learning, meaning, and identity*. New York: Cambridge University Press.

Wenning, C. J. (2005). Levels of inquiry: Hierarchies of pedagogical practices and inquiry processes. *Journal of Physics Teacher Education Online*, *2*(3), 3–11.

Wong, L.-H., & Looi, C.-K. (2011). What seams do we remove in mobile-assisted seamless learning? A critical review of the literature. *Computers & Education*, *57*, 2364–2381.

Woo, Y., & Reeves, T. C. (2007). Meaningful interaction in web-based learning: A social constructivist interpretation. *The Internet and Higher Education*, *10*(1), 15–25.