How designers create scalable science curricula

Anushree Bopardikar

HOW DESIGNERS CREATE SCALABLE SCIENCE CURRICULA

Anushree Dattaprasad Bopardikar

HOW DESIGNERS CREATE SCALABLE SCIENCE CURRICULA

DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
prof. dr. ir. A. Veldkamp,
on account of the decision of the Doctorate Board,
to be publicly defended
on Wednesday, 28th of June 2023 at 16.45 hours

by

Anushree Dattaprasad Bopardikar

born on the 17th of July, 1984
in Mumbai, India

This dissertation has been approved by:

Supervisor:
prof. dr. ir. S. E. McKenney

Co-supervisors:
dr. D. Bernstein
dr. B. Drayton

Cover design: Raghvendra Cowlagi
Printed by: Ipskamp Printing
Lay-out: Raghvendra Cowlagi
ISBN (print): 978-90-365-5682-8
ISBN (digital): 978-90-365-5683-5
URL: https://doi.org/10.3990/1.9789036556835

GRADUATION COMMITTEE:

Chair/secretary:	prof. dr. T. Bondarouk
Supervisor:	prof. dr. ir. S. E. McKenney Universiteit Twente, BMS, ELAN Teacher Development
Co-supervisors:	dr. D. Bernstein TERC, Massachusetts
	dr. B. Drayton TERC, Massachusetts
Committee Members:	prof. dr. B. J. R. van der Meulen Universiteit Twente, BMS, Knowledge, Innovation, and Transformation of Education and Society
	prof. dr. K. Schildkamp Universiteit Twente, BMS, ELAN Teacher Development
	prof. dr. M. Storksdieck Oregon State University
	prof. dr. Y. Kali University of Haifa
	prof. dr. N. M. Nieveen Technisch Universiteit Eindhoven

Table of Contents

Chapter 1
Introduction

This dissertation aimed to uncover designers' work behind science curricula designed for large-scale use. This chapter provides the rationale for a series of sub-studies that examined designers' thinking and action to create science curriculum products that yielded positive outcomes for students and teachers. As such, the chapter begins by articulating a vision for science education that is currently emphasized in reform initiatives for all students and the importance of high-quality curricular products to attain the vision. Next, challenges in designing successful science curricula at scale are explained, highlighting key issues that motivated the present study: supporting deep student learning of ideas and practices; supporting deep teacher learning for curriculum enactment; and supporting persistent curriculum use. Three research objectives related to these challenges are presented, focused respectively on supporting students' learning via real-world contexts; on supporting teachers' learning via educative curricula; and on supporting persistence in curriculum enactment. Thereafter, the chapter portrays the context of the study briefly and justifies using a multiple case study approach to conduct four sub-studies for pursuing the research objectives. The chapter closes with a brief overview of the sub-studies constituting the subsequent chapters of the dissertation.

1.1 Positioning the study

1.1.1 The role of curricula in science education today

Initiatives over the last decade to reform science education present an ambitious vision of supporting students to learn fundamental disciplinary ideas and practices through active participation and application of scientific knowledge (e.g., ACARA, 2012; National curriculum in England: Science programmes of study, 2013; National Research Council [NRC], 2012). For instance, the vision for reforms in the United States calls for significant student and teacher engagement through planning and conducting investigations and participating in discourse. Science curricular products are key vehicles to realize this vision because they can foster students' understanding of concepts and practices (e.g., Harris, Penuel, D'Angelo, DeBarger, Gallagher, Kennedy, et al., 2015; Pareja Roblin, Schunn, & McKenney, 2018). Furthermore, teachers need to draw on their knowledge of the subject matter and of instructional strategies to enact this vision in their classrooms. To that end, educative science curricula are crucial in intentionally supporting teachers' learning and enactment (in addition to students' learning) at elementary, middle, and high school grade levels (e.g., see Arias, Smith, Davis, Marino, & Palincsar, 2017; Cervetti, Kulikowich, & Bravo, 2015; Krajcik & Delen, 2017; Pareja Roblin et al., 2018; Williams, Krikorian, Singer, Rakes, & Ross, 2019).

As tools for action, (science) curricula reflect designers' thinking about how to support students and teachers. The present study investigates the intended curriculum, which is defined as a plan for learning (Taba, 1962). The intended curriculum refers to what designers hope will be implemented. This includes designers' vision for achieving specific learning outcomes (the scientific concepts and practices for student learning) and for specific participation and tasks through which students and teachers will engage with the content (Sandoval, 2014; Thijs & van den Akker, 2009). The intended curriculum also includes written artifacts like guidebooks and worksheets, which help students and teachers enact the vision (Goodlad, Klein, & Tye, 1979; Marsh & Willis, 2007; van den Akker, 2003, 2013; Walker, 1990).

Creating the intended curriculum involves a systematic process, consisting of three broad phases and specific activities within each phase (McKenney & Reeves, 2019). Designers typically begin with analyzing the problem and the target context through literature review and data about user needs (Edelson, 2002; Sánchez Tapia, Krajcik, & Reiser, 2018; Thijs & van den Akker, 2009). Then, they develop prototype solutions iteratively, including design features and principles (Miller, Severance, & Krajcik, 2021). Finally, designers evaluate the curriculum to inform revisions and for its effectiveness through expert appraisal (Sánchez Tapia et al., 2018; Thijs & van den Akker, 2009), pilots, and field tests (Clarke & Dede, 2009; McKenney & Reeves, 2019; Miller et al., 2021; Wiser, Smith, & Doubler, 2012). Whereas the phases are described here linearly, the overall process is cyclic and flexible (McKenney & Reeves, 2019). As insights from some activities and phases inform other activities and phases, designers usually engage in each multiple times, and they may do so in various sequences.

1.1.2 *Aim of this study*

The available literature focuses primarily on characteristics of high-quality science curriculum *products* (e.g., what makes a good teacher guide, or which features help teachers learn, etc.). Unfortunately, it offers little detailed guidance for the *process* which brings them to fruition. This is problematic from a scientific perspective because studying and designing curriculum require attending not only to the substance of the design, such as its content and objectives, but also to technical methods for reifying designers' ideals as written materials (Goodlad, 1994; Thijs & van den Akker, 2009). The lack of this knowledge is also a practical problem especially for novice designers who may struggle to identify pertinent considerations and activities for creating suitable curriculum products. Therefore, this study aims to generate knowledge about designers' work for crafting science curricula that can realize the designers' vision. To do so, the study investigated designers' reasoning and processes behind specific science curricula, and it links descriptions of these to the designed curriculum products, thereby making visible designers' rationales, considerations, and processes behind the completed products. In this way, the study offers examples to guide both novice and seasoned designers, especially those with limited access to relevant precedents that can inform their work in varied contexts (Howard, Boling, Rowland, & Smith, 2012; Lawson, 2004). The remainder of this chapter provides a brief review of (gaps in) the existing literature before describing the research design.

1.2 Conceptual underpinnings

The vision for science education described earlier is advocated for all students. This necessitates the creation of scalable curricula that can serve students and teachers in settings characterized by varied needs, wishes, and constraints. This is, of course, easier said than done. In creating a scalable curriculum, designers need to support deep student learning, which includes changes in students' understanding, integration and application of key scientific ideas and practices. This in turn typically requires deep teacher learning, which often involves supporting teachers to develop new understandings, views (i.e., knowledge and beliefs about the subject matter, student learning, pedagogy, etc.) and enactment of pedagogical principles. Teachers' learning is influenced by many factors, including what is referred to throughout this dissertation as curricular persistence – remaining amenable to enactment across time and place. Building on Coburn's dimensions of scale (2003), persistence attends to three dimensions: shift, sustainability, and spread. Supporting a shift in ownership involves transferring knowledge of and authority over the curricular intervention from external actors (i.e., the designers) to internal actors (i.e., the teachers as end users), so teachers can make suitable instructional decisions and adaptations. The shift in ownership, in turn, may be critical to the achievement of sustainability and spread of curriculum enactment. Sustainability involves efforts to continue curriculum enactment to achieve deep student learning and teacher learning in original or subsequent settings for substantial periods of time as designers' assistance fades gradually. Finally, spread involves expanding curriculum enactment beyond the field test sites, concerning use of not only the materials but also its underlying ideas within and across sites (Clarke & Dede, 2009; Coburn, 2003; Drayton, Bernstein, Schunn, & McKenney, 2020; McKenney & Reeves, 2019). As designers focus on depth and persistence in creating scalable curricula, they face specific challenges, each of which is elaborated below and motivates the present study. Figure 1.1 portrays a model of how depth and persistence interact in designing scalable curricula.

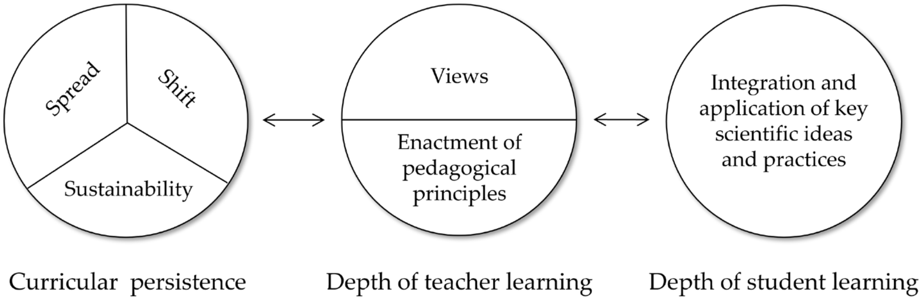


Figure 1.1: Model of how dimensions of scale interact (inspired by Coburn, 2003).

1.2.1 Supporting deep student learning of scientific ideas and practices

Consistent with the vision for science education described earlier, curricula seek to deepen students' learning. That is, they aim to help learners integrate and apply fundamental concepts, principles, or models, and the disciplinary practices through which these scientific ideas are generated to make sense of the world and to address problems that require scientific knowledge (Duschl, Schweingruber, & Shouse, 2007; Miller & Krajcik, 2021; NRC, 2012). This notion of deep student learning thus reflects a "knowledge-in-use" approach, emphasizing reasoning with scientific knowledge to perform cognitively demanding tasks, such as constructing explanations and designing solutions (Duschl et al., 2007; Krajcik, McNeill, & Reiser, 2008). To achieve this kind of deep learning, research advocates designing contextualized curricula that situate students' learning in authentic contexts (Krajcik & Blumenfeld, 2006). Two kinds of authentic contexts are foregrounded in the present study. The first context is engineering design-based projects in which students build artifacts to solve design problems that are situated in career settings (Vickers, 1998). Career contexts are crucial to prepare a broad range of students to pursue STEM-related post-secondary pathways. The second context is citizen science projects, in which students contribute to scientific research through data collection, analysis, and reporting (Bonney, Phillips, Ballard, & Enck, 2016). Citizen science contexts are crucial to engage students directly with key ideas and practices through first-hand investigations in addressing pressing (environmental) issues (Bonney et al., 2015; Houseal, Abd-El-Khalick, & Destefano, 2014).

Although authentic contexts can help students integrate and apply scientific ideas and practices, they pose design challenges because they require simultaneous attention to academic rigor, student interest, and opportunities for active exploration of phenomena as well as interactions with domain experts (Steinberg, 1998). To elaborate, the contexts need to be both appealing and cognitively engaging to deepen students' understanding (Blumenfeld, Kempler, & Krajcik, 2006). Furthermore, the content that can be explored through the contexts needs to be relevant to the discipline, to pedagogy, and to real-world applications, which calls for prioritizing core content that is aligned with curricular frameworks and central to addressing significant problems in communities or workplaces (Blumenfeld et al., 2006; Krajcik & Blumenfeld, 2006). How might designers serve students' interests while engaging them with pedagogically desirable subject matter? Finally, interactions with STEM practitioners can motivate students' participation in scientific practices (Zoellick, Nelson, & Schauffler, 2012), help them conduct their own projects (Gray, Nicosia, & Jordan, 2012), and understand how science is used in workplaces (Vickers, 1998). However, this requires careful orchestration to provide students with relevant, sufficient, and timely access to STEM expertise. How might designers plan for meaningful student exposure to actual models of STEM practice?

There is some literature to guide designers as they grapple with these kinds of questions in bringing authentic contexts into (standards-driven) classrooms. For example, the literature reports strategies for incorporating authentic questions and real-world problems (Edelson, Gordin, & Pea,1999; Kanter, 2010; Krajcik et al., 2008) and more generally on design principles, such as for coherence (Miller & Krajcik, 2019) and for cultural relevance (Sánchez Tapia, Krajcik, & Reiser, 2018). Yet there exists little guidance specifically on designers' thinking and action for contextualizing curricula in engineering design projects situated in career settings and in citizen science projects, two contexts that are crucial for deepening student learning, as mentioned before. Therefore, the first objective of this study is *to uncover designers' reasoning and processes used to deepen students' learning via real-world contexts based in (engineering design) careers and citizen science.*

1.2.2 Supporting deep teacher learning for curriculum enactment

Supporting deep student learning in terms of integration and application of scientific ideas and practices also calls for (supporting) deep teacher learning to blend the ideas and practices through an inquiry-based approach. That is, curricula need to help teachers develop their views – their knowledge and beliefs – to support their enactment of a science curriculum. Teachers' views of the meaning, nature, and importance of the subject matter; of how students think and come to learn the subject; and how to organize effective inquiry-based instruction are especially important in achieving deep impact (Coburn, 2003; Crawford, 2007). Teachers' enactment of the curriculum concerns the underlying principles for engaging students with the tasks and materials, including the overall approach and opportunities for students' inquiry, ways of representing the subject, and ways of eliciting and responding to students' thinking (Coburn, 2003). Teachers' views are important to address because teachers and curriculum designers may think differently from each other about enacting inquiry in classrooms (Crawford, 2007). Furthermore, teachers' understandings of science and their beliefs about learning as inquiry are interrelated and guide their work in teaching through inquiry (Anderson, 2002). Hence, designers need to address teachers' knowledge and beliefs as such and integrate (supports for) these into the practical context of their classrooms.

Educative curriculum materials instantiating content and tasks can address teachers' views and help them enact scientific inquiry in classrooms (Bismack, Arias, Davis, & Palincsar, 2015). However, planning for actual use — or enactment — is important, and includes helping teachers to clearly envision their own actions when using the curriculum (McKenney & Reeves, 2019). But communicating a vision of teachers' actions through educative materials is easier said than done because it involves key trade-offs. Namely, it requires thinking about how much explicit guidance to specify regarding content, activities, and intended student work as well as thinking about which resources to develop for the desired enactment (Cohen & Ball, 1999). And whereas highly specified and complete interventions may provide greater clarity, they may offer fewer opportunities for teachers to adjust instruction to their unique contexts. Thus, designers need to wrestle with ways to balance the needed educative support while providing room for teachers' agency to make appropriate adaptations (Drayton et al., 2020).

There is literature on features, heuristics, measures, and some processes for creating educative curricula (Davis & Krajcik, 2005; Davis, Palincsar, Arias, Bismack, Marulis, & Iwashyna, 2014; Davis, Palincsar, Arias, Smith, & Kademian, 2017; Kruse, Howes, Carlson, Roth, Bourdelat-Parks, et al., 2013; Miller et al., 2021; Roseman, Hermann-Abell, & Koppal, 2017). Yet, what is missing are insights into designers' thinking and action for simultaneously addressing multiple interconnected components of teacher learning, such as their knowledge of student thinking, of instructional strategies, and of the subject matter, to help teachers enact the underlying principles or approaches of a science curriculum (Magnusson, Krajcik, & Borko, 1999; Park & Chen, 2012). This gap is problematic because tackling the components simultaneously requires designer expertise from different disciplinary backgrounds, which can be complex to orchestrate. Therefore, the second objective of the study is *to uncover designers' reasoning and processes involving interdisciplinary expertise to deepen teachers' learning opportunities via educative curricula.*

1.2.3 *Supporting persistent curriculum use*

In addition to deepening students' and teachers' learning, curricula must also be amenable to enduring enactment in diverse settings. As noted earlier, doing so requires attention to the dimensions of curricular persistence (shift, sustainability, and spread). Further, research has shown that specific intervention characteristics can enable persistence, namely: added value, tolerance, compatibility, and clarity (McKenney & Reeves, 2019). Figure 1.2 shows the dimensions of curricular persistence and these four key enablers. The remainder of this sub-section elaborates (designers' challenges in relation to) these dimensions and the key enablers for achieving persistence.

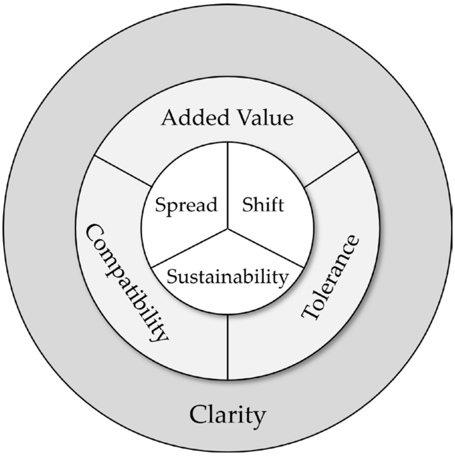


Figure 1.2: Dimensions of curricular persistence surrounded by their key enablers.

The *added value* of an intervention (such as a curriculum), pertains to the extent to which it is perceived as useful to perform routine tasks and offers perceptible and experiential benefits (Michel-Verkeke & Spil, 2013), in this case, related to students' learning as well as teachers' learning and practice (Fishman, Penuel, Hegedus, & Roschelle, 2011). Added value is crucial for attaining shift and spread, as it may motivate teachers to engage with and develop a solid understanding of the curriculum, thus prompting them to develop ownership over deepening and spreading the principles and practices embodied in it. For example, the curriculum may help teachers meet specific learning objectives emphasized in the school, district, or national frameworks but for which few resources exist to guide their practice.

Another enabler is *tolerance*, that is the precision with which "design intentions or core components must be enacted" to achieve the curricular goals (McKenney & Reeves, 2019; p. 172). The curriculum needs to tolerate intentional adaptations made by teachers while also supporting integrity of implementation, i.e., adjustments that maintain the underlying curricular vision and goals (Miller et al., 2021; Penuel, Phillips, & Harris, 2014). Tolerance is important for shift and sustainability as it can support teachers in continually making suitable instructional decisions in response to ongoing variations in their enactment contexts. Teachers often face changing curricular expectations, particular student needs and interests, and site-specific resources and constraints (Coburn, 2003). Therefore, designers must create adaptive curricula that can enable teachers to adjust to local needs and goals in a wide range of classroom settings (Drayton et al., 2020; Fishman & Krajcik, 2003; Squire, MaKinster, Barnett, Luehmann, & Barab, 2003). For example, educative materials may present exemplars and rationales communicating not only expectations of the intended content and pedagogical vision but also ways to own and adapt the curriculum fruitfully to teachers' own contexts (Thijs & van den Akker, 2009).

Yet another enabler is the curriculum's *compatibility* with user settings, needs, and concerns. Persistent enactment is difficult when sizeable gaps exist between curriculum requirements and the existing school policy, including local and state curriculum standards and testing practices, and teachers' capabilities, thus interfering with the usability of the intervention (Blumenfeld, Fishman, Krajcik, Marx, & Soloway, 2000). Compatibility is thus important for sustainability and spread because curricula that are consistent with the values and priorities of the target settings can (continue to) be relevant in original and subsequent settings. Compatibility also includes alignment with aspects of the broader system in which users operate, and which may be unalterable within the scope of the curriculum design project, such as national examinations. Furthermore, both objective and subjective compatibility are important (McKenney & Reeves, 2019). For instance, the content may be consistent with curricular frameworks and assessments of the target sites, and teachers may perceive curricular alignment with their own and their students' needs and inclinations.

Finally, *clarity* of curricular interventions is a crucial enabler of all dimensions, referring to the extent to which teachers can easily envisage their role and actions in implementation. Teachers need to be equipped with adequate knowledge to make suitable instructional decisions. Clarity can help teachers understand implications for what they need to know and be able to do as they seek to deepen their knowledge of the curriculum, to continue enacting it in varying contexts, and to extend curriculum use within and across sites. For example, clarity can be achieved by providing explicit guidelines, rationales, and specified procedures for classroom practice through exemplary materials for teachers (McKenney & Reeves, 2019). Doing so calls for identifying fundamental curricular elements especially related to the content, lesson preparation, tasks, and the teacher's role that may be at risk of premature modifications if the intervention is too complex or not sufficiently clear (Thijs & van den Akker, 2009).

The extant literature offers limited insights into how designers (approach these enablers to) pursue shift, sustainability, and spread of contextualized curriculum and educative materials, while striving to deepen students' and teachers' learning (see Drayton et al., 2020 for a similar argument). This gap is problematic because designing for scale involves multiplex decisions, which may be especially daunting for novice designers in creating contextualized curricula and/or educative curriculum materials. For example, to promote shift through educative curriculum materials, designers need to consider what guidance and options to offer and to do so in ways that are clear and tolerant to local adjustments, while ensuring that teachers have access to knowledge about the subject matter and practical implementation to make appropriate instructional decisions. Furthermore, to sustain curricula contextualized in citizen science, designers need to identify (fieldwork) opportunities that are compatible with school policy, resources, and constraints, including the need for specific pedagogical and scientific assistance, while ensuring schools' contributions to broader scientific research programs to maintain their interest. This in turn calls for melding considerations about the overall feasibility of citizen science with those about its underlying scientific value. Finally, achieving spread of curriculum contextualized in (engineering design) careers calls for selecting suitable career areas to represent vis à vis their accessibility in different locations and their relevance to school mandates and priorities operating in those locations. This in turn requires blending considerations about career contexts with those about school contexts in varied geographical regions that would add value and be compatible with teachers' settings. Therefore, the third objective of the study is *to uncover designers' reasoning and processes used to (support enablers that can) achieve persistence in curriculum enactment.*

1.3 Approach of the study

1.3.1 Research objectives

The present study aimed to unpack designers' thinking and processes behind scalable science curricula. Informed by gaps in the literature on the three key challenges in designing for scale, three specific research objectives (ROs) were formulated:

- **RO-A Students' learning:** To identify designers' rationales, considerations, and (team) processes for creating curricula that can deepen students' learning via real-world contexts. In this study, 'students' learning' refers to students' ability to integrate and apply key scientific ideas and practices via contexts where the subject matter is typically used.
- **RO-B Teachers' learning:** To identify how designers' rationales, considerations, and (interdisciplinary team) processes create educative curriculum materials with the potential to support teachers' learning. In this study, 'teachers' learning' pertains to their views and enactment of pedagogical principles underlying the curriculum.
- **RO-C Enactment persistence:** To identify how curriculum materials, designers' considerations, and (team) processes are geared towards supporting (enablers of) persistence in curriculum enactment. In this study, 'persistence' is characterized by shift in ownership, sustained use, and spread of the curriculum materials and underlying ideas.

1.3.2 Context of the study

This study took place within a broader investigation of designers' expertise and outcomes in relation to science curricula that were intended for large-scale use. Funded by the National Science Foundation in the United States, the investigation involved a mixed-methods approach to examine a variety of curricula and how they came to be. Other studies in this project provided broad analyses of the features of previously developed curricula that were supportive of teacher and learner outcomes at scale (Pareja Roblin et al., 2018) as well as how characteristics of government-funded science education curricula shifted along with changes in funding policies (Pareja Roblin, Schunn, Bernstein, & McKenney, 2018). By contrast, the qualitative approach taken in the present study focused on deep dives into a subset of the curricula to shed light on how designers tackled specific challenges.

1.3.3 Multiple case study approach

The present study involved qualitative inquiry into the work of curriculum designers to understand in depth their perspectives and processes – how they reasoned and the strategies they used – in generating scalable curricula that would respond to specific challenges in science education (Merriam, 2002). To this end, the case study method was followed to describe and analyze intensively designers' reasoning and action, explaining why and how designers produced particular curriculum representations to support students and teachers (Yin, 2014).

A multiple case study approach was used to pursue the ROs collectively, resulting in a set of four sub-studies. The case in each sub-study was a single science curriculum (see sections on Study design and Overview of the dissertation). Each RO was addressed through a combination of retrospective and participant-observation approaches. Two of the sub-studies involved retrospective analyses of previously completed curricula, while the remaining two sub-studies involved participant-observation of a live curriculum design project.[1] As elaborated below, this blend of approaches helped capture the complexity of designers' thinking and processes as manifested in multiple curriculum design endeavors.

The retrospective approach captured designers' reflections on processes, decisions, and challenges overcome in creating final products, yielding a detailed description of the curriculum as it was "envisioned by the designers, intended to be experienced, actually experienced by the users, (and) as it was brought to existence" (Howard et al., 2012, p.35). On the other hand, the participant-observation approach captured the design process as it was unfolding, recording events that would otherwise be relatively difficult to access, for example, details of how designers' ideas evolved in response to emergent needs and constraints. It also allowed for shaping the research process, such as convening meetings with designers to gather specific research data (Yin, 2014). Furthermore, through participant-observation, the author of the dissertation was immersed in the designers' routine work, which enabled her to "see from the inside" what they were experiencing as "meaningful and important" and how they performed design activities (Emerson, Fretz, & Shaw, 1995). The author's role as "dual citizen" in participant-observation thus facilitated deeper access and greater sensitivity to the designers' interactions and processes. The two approaches were deemed suitable to produce process-oriented worked examples explaining designers' rationales, considerations, and action taken in creating scalable science curricula with positive outcomes for students and teachers. These worked examples can aid other designers, especially novices, and are

---

[1] The two participant observation sub-studies were conducted on the same curriculum design project.

comparable to those in other fields where attempts by novices to understand and transfer knowledge and skills in solving problems can be enhanced by clarifying the "why" and the "how" of expert problem-solving (see Van Gog, Paas, & Merriënboer, 2014).

The study focused on three science curricula that were developed at an independent, non-profit educational research and development organization in the U.S (a work-based physics curriculum for high school; a discourse-centric curriculum on matter for primary school; and a citizen science ecology curriculum for middle school). This organization has a long history of promoting high-quality science education through innovative curricula for students and teachers with a broad range of learning needs and inclinations. The author of this dissertation had access to in-depth conversations with designers of the curricula and to their project documentation, which was crucial in collecting detailed data for the sub-studies.

1.3.4 Study design

As mentioned before, four sub-studies were undertaken to achieve the ROs. For RO-A, students' learning was addressed by sub-studies 1, 3, and 4. Sub-study 1 focused on retrospective analysis of a high school physics curriculum that situated students' learning in workplace contexts. Sub-studies 3 and 4 further enriched understanding of designers' work through participant-observation in the context of a middle school curriculum featuring citizen science and student-teacher-scientist partnership.

For RO-B, teachers' learning was addressed by sub-studies 2, 3, and 4. Sub-study 2 pursued this RO through a retrospective analysis of a primary school curriculum featuring many educative supports to teach about matter. Sub-study 3 uncovered through participant-observation how a school-based citizen science curriculum was created to support teachers in teaching about climate change. Sub-study 4 added to this understanding through participant-observation of designers' work to support student-teacher-scientist partnerships featuring citizen science.

For RO-C, enactment persistence was attended to in each of sub-studies 1, 2, 3, and 4. The findings about key features of curriculum materials and overarching designer considerations and processes from the four sub-studies were synthesized to pursue RO-C. Sub-studies 2, 3, and 4 shed light on designers' work for supporting shift in ownership; sub-studies 3 and 4 revealed designers' work for supporting sustainability; and sub-studies 1 and 4 highlighted designers' work for supporting spread. Table 1.1 presents an overview of the sub-studies in relationship to the ROs and case study approaches.

Table 1.1: *Mapping of sub-studies to the ROs and case study approaches.*

ROs	**Retrospective sub-studies**		**Participant-observation sub-studies**	
	1. Broadening Participation (physics curriculum)	2. Interdisciplinary Teams (matter curriculum)	3. Balancing Priorities (citizen science ecology curriculum)	4. Boundary Crossing (citizen science ecology curriculum)
RO - A: Students' learning	■		■	■
RO – B: Teachers' learning		■	■	■
RO – C: Enactment persistence	■	■	■	■

1.4 Structure of the dissertation

This section presents brief descriptions of the chapters that follow.

Chapter 2 (sub-study 1), entitled *Work-based Curriculum to Broaden Learners' Participation in Science: Insights for Designers*, reports how designers created a physics curriculum centered on authentic workplace contexts to support high school students with a broad range of inclinations to participate in science education. Data from semi-structured interviews with designers, project documents, and finished curriculum materials were gathered and analyzed retrospectively. This chapter has been published in *Research in Science Education*.

Chapter 3 (sub-study 2), entitled *Designing Educative Curriculum Materials in Interdisciplinary Teams: Designer Processes and Contributions*, reports collaborative interdisciplinary work behind educative curriculum materials to foster teachers' pedagogical content knowledge for inquiry-based teaching about matter. Semi-structured interviews with designers (science educators, cognitive psychologist, and practicing physicist) were conducted and project documents were gathered and analyzed retrospectively to uncover designers' discipline-based inputs. This chapter has been published in *Instructional Science*.

Chapter 4 (sub-study 3), entitled *Designer Considerations and Processes in Developing School-based Citizen Science Curricula for Environmental Education*, reports how designers (curriculum writers and practicing ecologists) supported students' learning about climate change in the context of citizen science. Data were gathered from researcher observations and reports, semi-structured interviews with designers, project documents, and curriculum materials through participant-observation and analyzed. This chapter has been published in *Journal of Biological Education.*

Chapter 5 (sub-study 4), entitled *Boundary Crossing in Student-Teacher-Scientist-Partnerships: Designer Considerations and Methods to Integrate Citizen Science with School Science*, reports how designers (curriculum writers and practicing ecologists) performed specific activities and created curriculum supports to help students, teachers, and scientists cross boundaries between the cultures of science and schooling for a scalable student-teacher-scientist-partnership (STSP). Data from multiple sources – researcher observations, project design documents, and semi-structured interviews with designers – were gathered through participation-observation and analyzed. This chapter has been published in *Instructional Science*.

Chapter 6 entitled, *Conclusion*, synthesizes and discusses findings from all four sub-studies to address each RO framing the dissertation. The strengths and limitations of the overall study approach are discussed. Based on these reflections, the chapter offers recommendations for future research, designer practice, and educational policy on designing scalable science curricula. Finally, the chapter closes with a commentary about the broader contributions of the research presented in this dissertation. Table 1.2 provides a visual overview of the dissertation chapters.

Table 1.2: Overview of dissertation chapters.

Chapter	**Curriculum Type**	**Sub-study Focus**	**Data Sources**	**Scientific Contribution**
1. Introduction	Positioning the study; presentation of ROs; overview of study design and sub-studies.			
2. Sub-study 1 RO-A	Physics curriculum situated in career contexts for high school	Describe representations of a work-based curriculum and underlying designer thinking and processes for aligning representations to serve students with varied academic and career inclinations.	Semi-structured interviews; project documents; finished curriculum materials.	Worked example and guidelines for curriculum product and design process to support learning in workplace contexts
3. Sub-study 2 RO-B	Learning progression-based curriculum on matter for elementary school	Portray collaborative interdisciplinary design processes behind educative curriculum materials to support teachers' pedagogical content knowledge.	Semi-structured interviews; project documents; finished curriculum materials.	Worked example and implications for conducting interdisciplinary design processes.

4. Sub-study 3 RO-A RO-B	Citizen science ecology curriculum for middle school	Identify evolution of designers' decisions and processes in tackling emergent needs and challenges behind a school-based citizen science curriculum.	Semi-structured interviews; project documents; in-progress curriculum materials; researcher observations and reports.	Worked example and implications for designing school-based citizen science curricula.
5. Sub-study 4 RO-A RO-B	Citizen science ecology curriculum for middle school	Articulate designers' considerations and methods to support boundary crossing processes between the cultures of science and schooling in Student-Teacher-Scientist Partnerships (STSPs) featuring citizen science.	Semi-structured interviews; project design documents; in-progress curriculum materials; researcher observations.	Worked example and insights on designers' thinking and action and practical guidelines to design for scalable STSPs
6. Conclusion	Reflection on syntheses of findings from sub-studies to address RO-A, RO-B, and RO-C; reflection on methods; recommendations for research, practice, and policy; and closing considerations.			

References

Anderson, R. (2002). Reforming science teaching. What research says about inquiry? *Journal of Science Teacher Education, 13,* 1–12.

Arias, A. M., Smith, P. S., Davis, E. A., Marino, J. C., & Palincsar, A. S. (2017). Justifying predictions: Connecting use of educative curriculum materials to students' engagement in science argumentation. *Journal of Science Teacher Education, 28*(1), 11-35.

Australian Curriculum, Assessment and Reporting Authority. (2012). *National Report on Schooling in Australia 2010*. Sydney: ACARA.

Bismack, A. S., Arias, A. M., Davis, E. A., & Palinscar, A. S. (2015). Examining student work for teacher uptake of educative curriculum materials. *Journal of Research in Science Teaching, 52*(6), 816–846.

Bonney, R., Phillips, T. B., Ballard, H. L., & Enck, J. W. (2016). Can citizen science enhance public understanding of science? *Public Understanding of Science, 25*(1), 2-16.

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2020). Work-based curriculum to broaden learners' participation in science: Insights for designers. *Research in Science Education*, *50*(4), 1251-1279.

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2021). Designing educative curriculum materials in interdisciplinary teams: Designer processes and contributions. *Instructional Science*, *49*(2), 249-286.

Bopardikar, A., Bernstein, D., & McKenney, S. (in press). Boundary Crossing in Student-Teacher-Scientist-Partnerships: Designer considerations and methods to integrate citizen science with school science. *Instructional Science*.

Bopardikar, A., Bernstein, D., & McKenney, S. (2021). Designer considerations and processes in developing school-based citizen-science curricula for environmental education. *Journal of Biological Education*, 1-26.

Blumenfeld, P., Fishman, B. J., Krajcik, J., Marx, R. W., & Soloway, E. (2000). Creating usable innovations in systemic reform: Scaling up technology-embedded project-based science in urban schools. *Educational Psychologist*, *35*(3), 149-164.

Blumenfeld, P. C., Kempler, T. M., & Krajcik, J. S. (2006). Motivation and cognitive engagement in learning environments. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 475–488). New York, NY: Cambridge University Press.

Cervetti, G. N., Kulikowich, J. M., & Bravo, M. A. (2015). The effects of educative curriculum materials on teachers' use of instructional strategies for English language learners in science and on student learning. *Contemporary Educational Psychology*, *40*, 86-98.

Clarke, J., & Dede, C. (2009). Design for scalability: A case study of the River City curriculum. *Journal of Science Education and Technology, 18*(4), 353-365.

Coburn, C. E. (2003). Rethinking scale: Moving beyond numbers to deep and lasting change. *Educational Researcher*, *32*(6), 3-12.

Cohen, D. K., & Ball, D. L. (1999). *Instruction, capacity, and improvement.* CPRE Research Report Series RR-43. Philadelphia, PA: Consortium for Policy Research in Education, University of Pennsylvania.

Crawford, B. A. (2007). Learning to teach science as inquiry in the rough and tumble of practice. *Journal of Research in Science Teaching*, *44*(4), 613-642.

Davis, E. A. & Krajcik, J. S. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher*, *34*(3), 3-14.

Davis, E. A., Palincsar, A. S., Arias, A. M., Bismack, A. S., Marulis, A. M., & Iwashyna, S. K. (2014). Designing educative curriculum materials: A theoretically and empirically driven process. *Harvard Educational Review, 84*(1), 24–53.

Davis, E. A., Palincsar, A. S., Smith, P. S., Arias, A. M., & Kademian, S. M. (2017). Educative curriculum materials: Uptake, impact, and implications for research and design. *Educational Researcher, 46*(6), 293–304.

Drayton, B., Bernstein, D., Schunn, C., & McKenney, S. (2020). Consequences of curricular adaptation strategies for implementation at scale. *Science Education*, *104*(6), 983-1007.

Duschl, R. A., Schweingruber, S. A., & Shouse, A. W. (2007). *Taking science to school: Learning and teaching science in grades K-8*. National Academies Press.

Edelson, D. C. (2002). Design research: What we learn when we engage in design. *Journal of the Learning Sciences, 11*(1), 105–121.

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences, 8*(3–4), 391–450

Emerson, R. M., Fretz, R. I., & Shaw, L. L. (1995). Writing ethnographic fieldnotes. Chicago: The University of Chicago Press.

Fishman, B. J., & Krajcik, J. (2003). What does it mean to create sustainable science curriculum innovations? A commentary. *Science Education*, *87*(4), 564-573.

Fishman, B., Penuel, W. R., Hegedus, S., & Roschelle, J. (2011). What happens when the research ends? Factors related to the sustainability of a technology-infused mathematics curriculum. *Journal of Computers in Mathematics and Science Teaching*, *30*(4), 329-353.

Goodlad, J. (1994). Curriculum as a field of study. In T. Husén & T. Postlethwaite (Eds.), *The international encyclopedia of education* (pp. 1262-1276). Oxford: Pergamon Press.

Goodlad, J., Klein, M., & Tye, K. (1979). The domains of curriculum and their study. In J. Goodlad (Ed)., *Curriculum inquiry: The study of curriculum practice* (pp. 43-76). New York: McGraw Hill Associates.

Gray, S. A., Nicosia, K., & Jordan, R. C. (2012). Lessons learned from citizen-science in the classroom. *Democracy & Education, 20*(2), 1-5.

Harris, C. J., Penuel, W. R., D'Angelo, C. M., DeBarger, A. H., Gallagher, L. P., Kennedy, C. A., ... & Krajcik, J. S. (2015). Impact of project-based curriculum materials on student learning in science: Results of a randomized controlled trial. *Journal of Research in Science Teaching*, *52*(10), 1362-1385.

Houseal, A. K., Abd-El-Khalick, F., & Destefano, L. (2014). Impact of a student-teacher-scientist partnership on students' and teachers' content knowledge, attitudes toward science, and pedagogical practices. *Journal of Research in Science Teaching, 51*(1), 84-115.

Howard, C. D., Boling, E., Rowland, G., & Smith, K. M. (2012). Instructional design cases and why we need them. *Educational Technology, 52*(3), 34.

Kanter, D. E. (2010). Doing the project and learning the content: designing project-based science curricula for meaningful understanding. *Science Education, 94*(3), 525–551.

Krajcik, J. S., & Blumenfeld, P. C. (2006). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 317–333). New York: Cambridge University Press.

Krajcik, J., & Delen, I. (2017). The benefits and limitations of educative curriculum materials. *Journal of Science Teacher Education, 28*(1), 1–10.

Krajcik, J. S., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education, 92*(1), 1–32.

Kruse, R., Howes, E. V., Carlson, J., Roth, K., Bourdelat-Parks, B., Roseman, J. E., & Flanagan, J. C. (2013) Developing and evaluating an eighth grade curriculum unit that links foundational chemistry to biological growth: Changing the research-based curriculum. Paper presented at the *NARST Annual International Conference*, Rio Grande, Puerto Rico, USA.

Lawson, B. (2004). Schemata, gambits and precedent: some factors in design expertise. *Design Studies, 25*(5), 443-457.

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teacher. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge* (pp. 95–132). Kluwer.

Marsh, C. J., & Willis, G. (2003). *Curriculum: Alternative approaches, ongoing issues* (4th edition). Upper Saddle River, NJ: Merrill/Prentice Hall.

McKenney, S., & Reeves, T.C. (2019). *Conducting educational design research*. London: Routledge.

Merriam, S. B. (2002). Introduction to qualitative research. In S. B. Merriam (Ed.), *Qualitative research in practice: Examples for discussion and analysis.* Jossey Bass.

Michel-Verkerke, M. B., & Spil, T. A. M. (2013). The USE IT-adoption-model to predict and evaluate adoption of information and communication technology in healthcare. *Methods of Information in Medicine, 52*(06), 475-483.

Miller, E. C., & Krajcik, J. S. (2019). Promoting deep learning through project-based learning: A design problem. *Disciplinary and Interdisciplinary Science Education Research, 1*(7), https://doi.org/10.1186/s43031-019-0009-6

Miller, E. C., Severance, S., & Krajcik, J. S. (2021). Motivating teaching, sustaining change in practice: Design principles for teacher learning in project-based learning contexts. *Journal of Science Teacher Education, 32*(7), 757-779.

Moscovici, H., & Nelson, T. H. (1998). Shifting from activity mania to inquiry. *Science and Children, 35*(4), 14–17.

National curriculum in England: Science programmes of study (2013, September 11). Gov.UK. Retrieved March 2020, from https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study/national-curriculum-in-england-science-programmes-of-study

National Research Council (NRC). (2012). A framework for K-12 science education: Practices, cross-cutting concepts, and core ideas. National Research Council: Washington D.C.

Pareja Roblin, N., Schunn, C., & McKenney, S. (2018). What are critical features of science curriculum materials that impact student and teacher outcomes? *Science Education*, *102*(2), 260-282.

Pareja Roblin, N., Schunn, C., Bernstein, D., & McKenney, S. (2018). Exploring shifts in the characteristics of US government-funded science curriculum materials and their (unintended) consequences. *Studies in Science Education*, *54*(1), 1-39.

Park, S., & Chen, Y. C. (2012). Mapping out the integration of the components of pedagogical content knowledge (PCK): Examples from high school biology classrooms. *Journal of Research in Science Teaching, 49*(7), 922–941.

Penuel, W. R., Phillips, R. S., & Harris, C. J. (2014). Analysing teachers' curriculum implementation from integrity and actor-oriented perspectives. *Journal of Curriculum Studies*, *46*(6), 751-777.

Pilot, A., & Bulte, A. M. (2006). The use of "contexts" as a challenge for the chemistry curriculum: Its successes and the need for further development and understanding. *International Journal of Science Education*, *28*(9), 1087-1112.

Roseman, J. E., Herrmann-Abell, C. F., & Koppal, M. (2017). Designing for the Next Generation Science Standards: Educative curriculum materials and measures of teacher knowledge. *Journal of Science Teacher Education, 28*(1), 111-141.

Sánchez Tapia, I., Krajcik, J., & Reiser, B. (2018). "We do not know what is the real story anymore": Curricular contextualization principles that support indigenous students in understanding natural selection. *Journal of Research in Science Teaching*, *55*(3), 348-376.

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

Schwartz, A. T. (2006). Contextualized chemistry education: The American experience. *International Journal of Science Education*, *28*(9), 977-998.

Squire, K. D., MaKinster, J. G., Barnett, M., Luehmann, A. L., & Barab, S. L. (2003). Designed curriculum and local culture: Acknowledging the primacy of classroom culture. *Science Education*, *87*(4), 468-489.

Steinberg, A. (1998). Real learning, real work: School-to-work as high school reform. New York: Routledge

Taba, H. (1962). *Curriculum development: Theory and practice*. New York: Harcourt, Brace & World.

Thijs, A., & van den Akker, J. (2009). *Curriculum in development*. Enschede: SLO Netherlands Institute for Curriculum Development.

Van den Akker, J. (2003). Curriculum perspectives: An introduction. In J. Van den Akker, W. Kuiper, & U. Hameyer (Eds.), *Curriculum landscapes and trends* (pp. 1–10). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Van den Akker, J. (2013). Curricular development research as a specimen of educational design research. In T. Plomp, & N. Nieveen (Eds.), *Educational design research* (pp. 52-71). Enschede, The Netherlands: SLO Netherlands Institute for Curriculum Development.

Van Gog, T., Paas, F., & Merriënboer, J. J. (2004). Process-oriented worked examples: Improving transfer performance through enhanced understandings. *Instructional Science, 32*(1), 83-98.

Vickers, M. (1998). Working to learn: Building science understandings through work-based learning. In A. Steinberg (Ed.), *Real learning, real work: School to work as high school reform* (pp. 109-127). New York: Routledge.

Walker, D. F. (1990). *Fundamentals of curriculum*. San Diego: Harcourt, Brace Jovanovich.

Williams, T. H., Krikorian, J., Singer, J. E., Rakes, C. R., & Ross, J. M. (2019). A high quality educative curriculum in engineering fosters pedagogical growth. *UMBC Faculty Development Center (FDC).*

Wiser, M., Smith, C. L., & Doubler, S. (2012). Learning Progressions as tool for curriculum development: Lessons from the Inquiry Project. In Alonzo, A. & Gotwals, A. (Eds.) *Learning progressions in science* (pp. 359–403). Boston: Sense Publishing.

Yin, R. K. (2014). *Case study research: Design and methods* (5th edition). Thousand Oaks, California: Sage Publications, Inc.

Zoellick, B., Nelson, S. J., & Schauffler, M. (2012). Participatory science and education: Bringing both views into focus. *Frontiers in Ecology and Environment: Citizen Science – new pathways to public involvement in research, 10(6),* 310-313.

Chapter 2
Broadening Participation

Around the globe, science education during compulsory schooling is envisioned for all learners regardless of their educational and career aspirations, including learners bound to the workforce upon secondary school completion. Yet, a major barrier in attaining this vision is low learner participation in secondary school science. Because curricula play a major role in shaping enacted learning, this study investigated how designers developed a high school physics curriculum with positive learning outcomes in learners with varied inclinations. Qualitative analysis of documents and semi-structured interviews with the designers focused on the curriculum in different stages - from designers' ideas about learning goals to their vision for enactment to the printed materials - and on the design processes that brought them to fruition. This revealed designers' emphases on fostering workplace connections via learning goals and activities, and printed supports. The curriculum supported workplace-inspired, hands-on design-and-build projects, developed to address deeply a limited set of standards-aligned learning goals. The curriculum also supported learners' interactions with relevant workplace professionals. To create these features, the designers reviewed other curricula to develop vision and printed supports, tested activities internally to assess content coverage, surveyed states in the U.S. receiving federal school-to-work grants and reviewed occupational information to choose unit topics and career contexts, and visited actual workplaces to learn about authentic praxis. Based on the worked example, this paper offers guidelines for designing work-based science curriculum products and processes that can serve the work of other designers as well as recommendations for research serving designers and policymakers.

This chapter is based on:

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2020). Work-based curriculum to broaden learners' participation in science: Insights for designers. *Research in Science Education*, *50*(4), 1251-1279.

International trends in educational reforms for compulsory schooling envisage that all learners participate in science education, irrespective of their academic and vocational interests (NRC, 2015; Osborne & Dillon, 2008; Tytler, 2007). This vision applies to a broad range of learners, from those aspiring to pursue advanced education and careers in STEM fields to those seeking to join the workforce after completing compulsory education. In bringing this vision to fruition, educators face a sizable roadblock with low numbers of learners pursuing science courses during secondary schooling, a serious problem noted in many countries. For example, 64% of secondary school graduates in the U.S. did not complete even one course credit in physics, and 30% did not complete it in chemistry in 2009 (Kena et al., 2016). Similarly, only 14% of year 12 learners in Australia studied physics, 18% studied chemistry, and 24% studied biology in 2012 (Kennedy, Lyons, & Quinn, 2014; Marginson, Tytler, Freeman, & Roberts, 2013). In the UK and elsewhere in Europe, countries are also experiencing challenges with attracting learners to science and technology education (SjØberg & Schreiner, 2005; Smith, 2011). Thus, an important challenge faced by schools and curriculum developers internationally is finding ways to serve learners with varied career inclinations, and reaching out especially to those who are presently disinclined to engage with science.

To that end, a key issue to address is learners' perceptions of the lack of relevance of science and technology curricula. International recommendations advocate elucidating how learning science can give learners access to various careers that are attractive to them (Osborne & Dillon, 2008), sometimes by promoting interactions between learners and STEM professionals (Marginson et al., 2013). Further, experts stress the development of instructional approaches that promote applications of scientific concepts in real world contexts, and cultivate reasoning and problem-solving (Tytler, 2007), for example, by embedding engineering design activities in school curricula (Marginson et al., 2013). Engineering practices and design problems are seen as a means to deepen learners' understandings of scientific ideas, to make science learning meaningful, and to highlight the value of science in everyday lives and society (NRC, 2012, 2013). To enact this vision, teachers are advised to include performance tasks, open-ended questions and discussions that encourage exploration of ideas, instead of eliciting only right answers (NRC, 2015).

2.1 Problem statement

Work-based science curricula at the secondary school level can help address the urgent need for developing critical thinking and problem-solving competencies in all learners, but these are challenging to create. One main difficulty lies in generating learning experiences that are authentic, appealing, and rigorous – all of which are required to promote *deep understanding* and *rich performance*. Curricula should help learners comprehend and integrate key concepts, principles and models to make sense of phenomena in the world (Duschl, Schweingruber, & Shouse, 2007). They need to help learners develop knowledge of the practices by which these ideas are created and utilized (Duschl et al., 2007; NRC, 2012). Finally, curricula must also invite learners to demonstrate their depth of understanding through rich performances that involve reasoning and applications of scientific ideas and practices via cognitively demanding tasks (Tekkumru-Kisa, Stein, & Schunn, 2015).

To create such curricula, designers need rich exemplars describing products and processes linked to finished designs (Howard, Boling, Rowland, & Smith, 2012). Existing literature from the fields of instructional design (e.g., Gustafson & Branch, 2002) and curriculum design (e.g., Thijs & van den Akker, 2009) sheds some light on key processes for creating instructional products. Further, the science education literature has described design processes to address challenges in supporting learners (Edelson, Gordin, & Pea, 1999; Kanter, 2010; Krajcik, McNeill, & Reiser, 2008), and to create educative curriculum materials for teachers (Davis et al., 2014). However, literature that offers fine-grained examples or design process guidelines for work-based science curricula is severely lacking. This, together with the fact that designers themselves often have limited knowledge of suitable workplace problems and practices that are of interest to the majority of learners, means that designers struggle to create work-based curricula that draw on authentic and appealing occupational contexts. Thus, there is a need for robust examples of work-based curricula, as well as insight into the processes that bring them to fruition.

2.2 Goal and significance of the study

The goal of the study is to produce a worked example of a powerful work-based curriculum that aimed to broaden learners' participation in science, as well as of its design processes. Akin to process-oriented worked examples in other fields (see Van Gog, Paas, & Merriënboer, 2004), this example aims to reveal the rationales and reasoning in designers' thinking about their product, and to demonstrate key strategies that they used to create it. Whereas generic resources exist, such as instructional design models (Gustafson & Branch, 2002) or case examples for teaching instructional design (Ertmer & Quinn, 2007), this study speaks to the need for rich exemplars of design products and their underlying processes, making accessible designers' decisions and reflections on the finished products (Howard, 2013; Howard et al., 2012). By offering insight into the designer reasoning behind a work-based curriculum for all learners that is also aligned with international literature, this worked example can be valuable to science educators internationally.

2.3 Context of the study

The worked example focuses on a work-based curriculum which showed evidence of positive learning outcomes for learners with different aspirations: four-year college, two-year college, vocational-technical education, and workforce-bound (see Methods for a full set of curriculum selection criteria). Although the designers believed their product was suitable to all learners, including college-bound learners who were eager to explore different technical careers, the curriculum was targeted especially at learners who were generally disinclined to study physics. These learners typically opted out of science courses after two years of secondary school; many of them were turned off by traditional abstract science pedagogy and did not find science engaging or relevant. The curriculum used an innovative approach to make physics relevant to learners' lives and potential careers beyond school. It linked standards (reforms)-based science learned in school with science applied in different work settings related to engineering and technology, and used engineering design projects in the classroom to engage learners with scientific knowledge, practices, and problems tackled by engineers and technicians. The curriculum contained a teacher guide, learner resource book, and learner activity sheets called job sheets. These materials covered five units, and each unit lasted about six weeks. When enacted as a sequence, the units covered a full year of secondary school physics. The following section describes the theoretical underpinnings for the retrospective analysis of this curriculum.

2.4 Theoretical framework

2.4.1 Curriculum manifestations

Designers' ideas for helping learners attain deep understanding and rich performance in science manifest in different forms of the curriculum. This study focuses on three curriculum manifestations that are particularly salient to the work of designers: (a) the *outcomes* designers intend to achieve, (b) their *vision* for enactment in the learning environment, and (c) the *written* materials specifying and supporting teaching and learning activities. Referred to in curriculum theory as 'curriculum representations,' (Goodlad, Klein, & Tye, 1979; van den Akker, 2003; Walker, 1990), this notion emphasizes that curricula are reified in different ways. To produce high quality curricula, the manifestations need to be consistent with one another (McKenney, Nieveen, & van den Akker, 2006). This section describes the meaning and importance of these manifestations, and designers' challenges in relation to each.

2.4.1.1 Intended Outcomes (IO)

The IOs are learning objectives that designers set out to achieve, namely the scientific ideas and practices they hope learners would comprehend. These are positioned in relation to the overarching vision (Thijs & van den Akker, 2009), and can be articulated as performances specifying how learners should apply their understanding of scientific ideas and practices (Krajcik et al., 2008; Rivet & Krajcik, 2004).

Attention to IOs allows designers to select specific phenomena that learners can study to understand the target scientific ideas and practices (Krajcik et al., 2008), and to identify alternative learner ideas that will need to be addressed in the curriculum materials (Rivet & Krajcik, 2004). Designers use IOs also to plan assessments so they can measure the intended performances (Krajcik et al., 2008).

Designing IOs in science curricula for all learners involves particular challenges. For example, science standards in policy documents cover a broad range of content, but treating scientific ideas deeply requires selecting fewer standards to formulate the IOs (Krajcik et al., 2008). Further, sequencing of scientific ideas targeted in the IOs may need to deviate from the traditional disciplinary structure to make them coherent and relevant to the particular learning activities emphasized in the curriculum (Sherin, Edelson, & Brown, 2004).

2.4.1.2 Envisioned Enactment (EE)

EE refers to instructional activities designed to help learners attain the IOs. These are tasks to engage learners with specific scientific ideas and/or practices

(Tekkumru-Kisa et al., 2015). When designers envision enactment, they may plan instructional activities with particular structures (Songer, 2006) and patterns to support learners in eliciting and integrating ideas (Linn, Clark, & Slotta, 2003); inquiry-based investigation projects with driving questions (Edelson et al., 1999; Linn et al., 2003; Squire, McKinster, Barnett, Luehmann, & Barab, 2003); design projects for learners to perform (Kanter, 2010; Kolodner et al., 2003; Sadler, Coyle, & Schwartz, 2000); teachers' role in facilitating teacher-learner discussions (Kolodner et al., 2003); and organizational matters like location and learner grouping (Thijs & van den Akker, 2009). Attention to instructional activities is critical because these influence not only the disciplinary knowledge that learners comprehend but also how deeply learners engage with and apply that knowledge (Tekkumru-Kisa et al., 2015).

Designing instructional activities for learners with different career inclinations requires attending to authenticity, engagement, and connections with scientific principles. Authentic practices are typically complex and unfamiliar to novices, and it is challenging for designers to reduce the complexity of those practices whilst preserving their core elements (Edelson & Reiser, 2006). Further, whereas authentic practices and sustained investigation can promote learners' understandings (Edelson et al., 1999), these activities demand high learner motivation. Finally, design tasks can motivate learners but it is often difficult to maintain strong connections to underlying scientific principles while they engage in artifact construction (Kolodner et al., 2003). Specifically, designers need to ensure all target content is useful in performing the tasks, but this is challenging because learners may find the content relevant but not necessary to complete the tasks (Kanter, 2010).

2.4.1.3 Written Curriculum (WC)

The WC embodies designers' ideas about EE and IOs (Thijs & van den Akker, 2009). The WC is crucial because learners need support to perform scientific practices (Lee & Butler, 2003), and the extent of written support influences their understandings of the practices (McNeill, Lizotte, Krajcik, & Marx, 2006; Songer, 2006). Designers create different types of print-based and/or digital materials to support learners. For example, to guide learners' investigations of real-world scenarios, learner materials contain prompts to help them plan experimental procedures (e.g., Kolodner et al., 2003), to determine key evidence in analyzing data (Songer, 2006), to construct explanations based on evidence and scientific principles (e.g., McNeill et al., 2006), and to monitor their progress in conducting scientific inquiry (Linn et al., 2003).

The WC typically also contains guidance for teachers to promote learners' understandings of scientific concepts and practices. Materials such as printed teacher guides facilitate teachers' daily instructional practice (Davis, Janssen, & Van Driel, 2016). The written supports may provide teachers with procedural assistance in implementing the curriculum and supporting learners' understandings, for example, strategies or tips for orchestrating whole class discussions (Pareja Roblin, Schunn, & McKenney, 2018). Curriculum materials may also contain educative elements that are designed explicitly to promote teachers' knowledge of scientific ideas and disciplinary practices (Davis & Krajcik, 2005). The materials may help teachers anticipate learners' alternative ideas about scientific concepts, and indicate how teachers can use suitable language and thought experiments to respond to learners' ideas (Davis & Krajcik, 2005). The materials may also indicate what scientific content to emphasize during instruction (Davis et al., 2014). Additionally, the WC may clarify the nature and importance of scientific practices (McNeill & Krajcik, 2008), and why learners should engage in these (Davis et al., 2014). The materials may also delineate characteristics of high quality scientific practices, and suggest general and specific strategies to enact these practices (Bismack, Arias, Davis, & Palincsar, 2015; Davis et al., 2014). The educative elements may appear as overviews with background information or embedded as supports within specific lessons (Bismack et al., 2015; Davis et al., 2014). To generate meaningful experiences for learners, altering tasks and objectives to suit local classroom contexts is critical; hence, curricula need to support teachers in making necessary adjustments (Barab & Luehmann, 2003; Squire et al., 2003).

In developing the WC, a key challenge for designers is ensuring that learners have just-in-time access to critical information for conducting sustained investigations (Edelson et al., 1999). Moreover, scientific practices such as analyzing data and constructing scientific explanations are difficult to perform without suitable hints in learner materials (McNeill et al., 2006; Songer, 2006). Nevertheless, creating prompts and hints at the right level of detail is challenging because too much specificity may turn scientific inquiry into recipes for actions, whereas too little may limit learners' engagement with inquiry (Linn et al., 2003).

Attending to teacher materials is crucial for achieving impact on learner outcomes (Pareja Roblin et al., 2018). Well-designed supports can influence teachers' curricular planning and actual instructional practices during enactment, and thereby the opportunities available to learners (see Davis et al., 2016 for review). In this regard, curriculum materials may be considered as tools which, together with teachers' own 'pedagogical design capacity' (Brown, 2009; Remillard, 2005) enable them to create new or revised learning opportunities. Hence, as good tools support craftsmanship, good teacher materials support teacher customization efforts. Yet, designers struggle to balance the need for support against the risk of overloading users with too much information. For example, teachers may not always be familiar with enacting scientific practices (Knight-Bardsley & McNeill, 2016; Krajcik & Blumenfeld, 2006; Simon, Erduran, & Osborne, 2006) or engineering design approaches (Mehalik et al., 2008), and may even hold misconceptions about the nature of scientific practices (Zangori, Forbes, & Biggers, 2013). As a result, designers are tasked with creating usable written supports with suitable hints and just-in-time information for learners, as well as relevant and practical guidelines on pedagogical content knowledge for teachers to facilitate learners' understandings.

2.4.2 Design processes to yield IO, EE and WC

Each of the IO, EE, and WC manifestations of a curriculum product are generated through systematic, iterative design processes including the core phases of analysis, development, and evaluation (see for instructional design processes Branch & Merrill, 2012; Gustafson & Branch, 2002). This study examines designers' specific activities in these phases that are vital in generating the three aforementioned manifestations of curricula (IO, EE, WC) that can foster deep understanding and rich performance in learners with a broad range of aspirations.

2.4.2.1 Analysis

Designers often begin with this phase to understand the problem and scope for improvement (Thijs & van den Akker, 2009). They study the needs of target learners and teachers, and the settings where the curriculum will be used (McKenney & Reeves, 2012; Edelson, 2002), as well as the target tasks to determine what knowledge and skills learners should develop to perform the tasks (Smith & Ragan, 1999). Salient activities are reviewing literature to understand the problem and how others have addressed similar problems (McKenney & Reeves, 2012). For example, designers review subject matter in policy documents such as science standards to identify what content needs to be taught (Krajcik et al., 2008; Rivet & Krajcik, 2004; Songer, 2006) and examine existing curriculum materials to understand what opportunities are specified for learning, assessment, and teacher and learner participation (Davis et al., 2014). Designers also gather data to assess needs and context of target audience (Edelson, 2002), through, for example, questionnaires given to school personnel (McKenney & Reeves, 2012). Based on insights in this phase, they define the problem, formulate overall goals, and generate preliminary design specifications and requirements (McKenney & Reeves, 2012; Edelson 2002) to determine the IOs, envision learning activities (EE), and plan the WC.

2.4.2.2 Development

In this phase, designers explore ideas for solutions, map their details, and build prototype solutions (McKenney & Reeves, 2012). They take concrete steps to address the goals and contextual considerations (Edelson, 2002), striving to design instruction that is effective, efficient, and pertinent to the target audience (Gustafson & Branch, 2002). Salient activities include reviewing policy documents such as standards and benchmarks in national, state or district level science frameworks (Krajcik et al., 2008; Rivet & Krajcik, 2004; Songer, 2006), and prior research to derive IOs and sequences of learning experiences (Songer, 2006), and studying the literature to identify strategies by which teachers can support learners (Davis et al., 2014).

Designers also gather input from scientists to identify important scientific facts in content areas (Songer, 2006), and to learn about authentic scientific practices (Edelson et al., 1999). They gather feedback from teachers to situate content and IOs in real world contexts (Kracik et al., 2008; Rivet & Krajcik, 2004), to envision (EE) performance tasks that require application of target science content (Kanter, 2010), and to generate instructions and questions for learning activities (Edelson et al., 1999). They revisit IOs to consider sequence of concepts and requisite knowledge that should be supported (Krajcik et al., 2008), and analyze performance tasks conceptually to assess the extent of target science content that learners must apply in performing the tasks (Kanter, 2010). Based on the activities in this phase, designers specify measurable IOs (Gustafson & Branch, 2002), select content to be learned (Smith & Ragan, 1999), envision enactment of learning tasks (EE) and their sequences to help learners attain the IOs (Krajcik et al., 2008; Songer, 2006), and produce the WC as per design specifications (Gustafson & Branch, 2002).

2.4.2.3 Evaluation

Finally, in this phase, designers test the curriculum for both formative and summative purposes - gathering data to determine required revisions, and to assess overall effectiveness of the curriculum (Branch & Merrill, 2012; Gustafson & Branch, 2002). Both partially designed and complete versions of the WC are evaluated (see survey of instructional design models in Gustafson & Branch, 2002). Salient activities are external expert appraisal (Krajcik et al., 2008; Thijs & van den Akker, 2009); pilots of early prototypes of the WC, and tryouts or field tests of more mature prototypes in classrooms (McKenney & Reeves, 2012). Designers observe teachers' enactments of materials (Davis et al., 2014) and learners' engagement in instructional activities (Edelson et al., 1999), examine learners' gains on tests of learning outcomes (Clarke & Dede, 2009; Rivet & Krajcik, 2004), and gather feedback from interviews with teachers (Clarke & Dede, 2009; Davis et al., 2014). Based on evaluation data, designers make needed changes to the curriculum manifestations (Branch & Merrill, 2012; Gustafson & Branch, 2002).

2.5 Research question

As the preceding literature review shows, prior work in the fields of instructional design and curriculum design reveals critical processes that guide the creation of instructional products. Similarly, the literature on science education describes curriculum manifestations and key design processes that can support learners and teachers. But these bodies of literature do not provide detailed insights into the manifestations of a work-based science curriculum for learners with different career inclinations, nor into the processes that help designers align these manifestations. To support science curriculum designers, therefore, this study sought to identify and analyze key design decisions in the development of a high school work-based physics curriculum that yielded positive outcomes for learners with varied career aspirations. In so doing, it aimed to produce a worked example of the curriculum product and its design processes, and to derive guidelines that could serve future work. To reach this goal, the following main research question was formulated: *What characterizes the manifestations (IO, EE, WC) of a work-based science curriculum and how do design processes (analysis, development, and evaluation) contribute to designers' thinking about alignment among these manifestations?*

2.6 Methods

2.6.1 *Case sampling, characteristics and relevance*

This research comprised a qualitative interpretive case study (Merriam, 1988) of one high school physics curriculum developed previously. This method was chosen because the desired outputs were a worked example detailing a finished curriculum product and its design process (Howard et al., 2012), as well as guidelines derived from this description. The study reported in this paper was conducted in the U.S., and emerged out of a larger investigation that used the following criteria to examine the manifestations and design processes of powerful science curricula developed for large scale use: (a) designed for a K-12 audience, (b) stand-alone classroom curriculum (in contrast to supplementary or out-of-school curriculum), (c) availability of key project staff and relevant documentation, (d) intention to support deep understanding and rich performance in science, and (e) evidence of positive learning outcomes for learners. Based on these criteria, six potential cases were identified. From them, the present case was selected for its insights into designing work-based science curriculum for all learners.

The case was a full-year senior secondary school curriculum for physics credit for grades 10, 11 or 12. The researchers were able to contact the designers via email and gather documentation from the designers' organization. The curriculum was designed to help learners comprehend and apply physics concepts and the engineering design process. The curriculum was field tested with learners indicating different academic and vocational aspirations. Whereas most learners aspired to join four year colleges, many planned to also join the workforce after high school, and some learners aspired to join two-year colleges or vocational-technical programs. The curriculum project's reports to the funding agency stated that in field trials held in six states in the U.S., learners using this curriculum performed at higher levels on science content and process skills items from the National Association of Educational Progress (NAEP) compared to the national NAEP norms.

The curriculum was developed over a five-year period at an independent, non-profit, educational research and development organization in the U.S. Throughout its history, the organization has been committed to making high quality education accessible to learners with diverse needs and interests, and to broaden learners' participation in science. As a result, many curricula developed at this organization seek to expand learners' access to fundamental science education. The curriculum was subsequently published by a commercial publisher. It has been in commercial publication since 2006, and remains available through the publisher's catalogue and other bookstores.

The curriculum responded to two reform movements originating in the 1990s in the U.S.: (1) the National Science Standards advocating rigorous academic content with an inquiry orientation (NRC, 1996), a precursor to the current K-12 Science Framework on integrating scientific concepts and practices (NRC, 2012); and (2) the school-to-career movement (Goldberger & Kazis, 1996) aimed at equipping learners with basic competencies for potential careers. The curricular mission was to teach standards-aligned science content in the context of broad career areas of interest to learners. Although the curriculum was inspired by educational policies in the U.S. from nearly two decades ago, and was developed prior to the Next Generation Science Standards (NGSS Lead States, 2013), its focus on teaching physics in the context of careers in engineering and technology renders this curriculum and its underlying design process pertinent to the current international trends in science education reform that were described earlier. These include the importance of situating learning in real world settings (Tytler, 2007), increasing learners' awareness of a wide range of STEM related careers in society (Marginson et al., 2013), and making school science engaging and accessible to all learners (Osborne & Dillon, 2008). Further, challenges in reaching learners with diverse inclinations persist, as a major hurdle in preparing learners for successful careers in the 21st century includes learners dropping out of school due to perceived lack of connections between school learning and the workforce (Symonds, Schwartz, & Ferguson, 2011).

2.6.2 Data sources

In accordance with recommendations to use evidence from multiple data sources in case study research (Yin, 2014), this study used project documents, the commercially published curriculum materials, and transcripts of interviews conducted with the curriculum development team to investigate each manifestation and related design processes. Table 2.1 describes the data sources and information obtained.

Table 2.1: Data sources used to examine curriculum manifestations (CM) and design processes (DP).

Data Sources	CM	DP
Project documents (grant proposal, drafts of WC, designers' memos, progress reports)	IO; EE; WC	Analysis, development, and evaluation phases
Commercially published WC (teacher guide, learner resource book, job sheets)	WC	-
Transcripts of interviews	IO; EE; WC	Development and evaluation phases

Legend: CM = Curriculum Manifestations; IO = Intended Outcomes; EE = Envisioned Enactment; WC = Written Curriculum; DP = Design Processes

2.6.3 Participant sampling and characteristics

A combination of purposeful and referral sampling was used to recruit participants with different roles and stages of work on the curriculum project. The project leader of the curriculum served as an informant to guide sampling choices (Yin, 2014) by providing an initial list of designers, and additional referrals were obtained from them. Six members of the curriculum team participated in the study: the project leader, two internal formative evaluators, and three curriculum writers. See Table 2.2 for participants' roles, stages of work, and alphanumeric codes to distinguish among participants. In the results section, participants are identified by their roles and alphanumeric codes (P1 through P6).

Table 2.2: Participant roles and timeline of their work on the curriculum design project.

Participant roles	Stages of work	Alphanumeric codes
Project leader	Entire duration[1]	P1
Internal formative evaluator	Early	P6
Internal formative evaluator	Late	P3
Curriculum writer	Early	P2
Curriculum writer	Early	P5
Curriculum writer	Late	P4

[1] Served as project leader after initial leader left, but was involved throughout the early, mid and late stages of work.

2.6.4 *Procedure*

The data collection involved three steps. First, to understand the curriculum goals and materials, the researchers obtained project documents and commercially published curriculum materials from the organization where the curriculum had been developed. The researchers created a project timeline to represent key design activities and outputs, and a list of relevant documents, publications and contact information of the curriculum team. Second, the researchers met the project leader, one curriculum writer, and one internal formative evaluator in a single session. The purpose of this meeting was to verify and refine the description of the curriculum goals and project timeline prepared by the researchers. During the meeting, the draft project timeline served to aid the participants' memory and guide the initial conversation about their work. Third, six prolonged interviews (Yin, 2014) were carried out, one with each of the six participants. Documents describing the curriculum goals and materials, and the refined project timeline were emailed to the participants prior to the interviews. The interviews followed a semi-structured protocol comprising four main questions, three on the curriculum manifestations (IO, EE, WC) and one on design processes (analysis, development, evaluation). Additionally, a set of prompts accompanied each main question and was used to ask for more information and/or to clarify the question. Table 2.3 shows the main questions and sample prompts. The interviews lasted approximately two hours per respondent, were completed over one or two sessions as per the respondents' preferences, and conducted via face-to-face and/or electronic media. The project leader was interviewed last to also clarify information from other respondents. All interviews were audiotaped and transcribed, resulting in six transcripts.

Table 2.3: Sample of interview questions and prompts.

	IO	**EE**	**WC**	**DP**
Questions	What kinds of deep understanding and rich performance in science were important to you and why?	In what ways did you endeavor to elicit your ideas about deep understanding and rich performance in the classroom?	How were your ideas about deep understanding and rich performance manifested in the written curriculum?	How did your design process and activities during *analysis, development* and *evaluation* facilitate the creation and refinement of these manifestations in the curriculum?
Sample Prompts	Which scientific concepts and practices were important?	How did you imagine learners would build understandings of scientific concepts through classroom activities?	How did your curriculum support learners' deep understandings of scientific concepts?	Analysis: How did you learn about the target audience, context, and what was important for them to learn?

Legend: IO = Intended Outcomes; EE = Envisioned Enactment; WC = Written Curriculum; DP = Design Processes

2.6.5 *Data analysis*

The document analysis was conducted in two phases. In the first phase, as stated earlier, project documents and commercially published curriculum materials were examined to create descriptions of curriculum goals, materials, and timeline of design work. This analysis was performed to guide the preliminary meeting and verify the information with a subset of the curriculum team. In the second phase, the researchers analyzed project documents to "corroborate and augment" findings from the prolonged interviews (Yin, 2014, p.107) and to generate additional findings. Specifically, the documents were used to confirm participants' descriptions of curriculum manifestations and design processes, extend those descriptions with details and examples, and to extract new information about how the designers worked to support deep understanding and rich performance.

The six interview transcripts were coded deductively with a formal scheme based on the conceptual framework and research questions (Miles & Huberman, 1994), capturing curriculum manifestations and design processes. A code of 'none' was applied to data that were not codable. The coding scheme was revised iteratively. The first author and another researcher independently practiced coding one complete transcript at a time. The unit of coding was a single sentence. Discrepancies in coding were resolved through discussions, and final coding decisions were established through consensus. This continued until the coders achieved an acceptable level of inter-rater reliability (Cohen's Kappa was approximately 0.87[2]). Table 2.4 presents the codes, their descriptions, and sample quotations from the interview data.

Table 2.4: Codes used in the data analysis.

Codes	Code Descriptions	Code Examples
IO	The learning goals in science that the designers set out to achieve	"You know, rather than it being a series of sort of disconnected reading assignments, the goal was to give students and opportunity to build their understanding of concepts, and at the same time, to help students integrate those concepts"
EE	The designers' vision of learning opportunities that would help learners attain the intended outcomes	"So we imagine that kids are working together, and to understand concepts by doing things, and that the teacher is watching and guiding, but not lecturing at all, actually"
WC	The manifestation of the designers' intentions in written curriculum materials for learners and teachers	[referring to the Teacher's Guide] "So this is a question saying, you know, like we've learned something about metals, and that metals have electrons. So what if you don't have the electrons? Then what happens if you try to put current through something. So there's like a specific

---

[2] The Cohen's Kappa was computed for a total of 13 codes used in the larger investigation from which this study emerged. The study focuses on four of these codes that were relevant to the designers' work on fostering deep understanding and rich performance in learners.

		question saying, well what do you think's going to happen?"
DP	The activities performed in *analysis, development* and *evaluation* phases of the design process to create and refine IO, EE, and WC	"And I believe we interviewed people there and asked them about the kinds of things that they worked on, and in some cases, we could say, what kind of science is important here?"

Legend: IO = Intended Outcomes; EE = Envisioned Enactment; WC = Written Curriculum; DP = Design Processes

2.7 Results

The designers contextualized reforms-aligned physics content in workplace settings related to a variety of careers in engineering and technology. Throughout their design process, they prioritized workplace connections consistently, attended to authenticity, appeal, and rigor of the science content, and developed instructional supports to deepen learners' understandings of physics concepts and engineering design practices. As an advanced organizer, Table 2.5 summarizes the curriculum manifestations (IO, EE, WC) embodying workplace connections, as well as the design processes linked directly to each of these. Thereafter, corresponding to each row in the table, detailed findings are presented.

Table 2.5: Curriculum manifestations (CM) and design processes (DP) for fostering workplace connections.

CM	**DP**		
	Analysis	Development	Evaluation
IO Learners comprehend, integrate limited set of key physics concepts and engineering design processes; show rich performances where they apply relevant concepts and practices to solve unit projects; understand that science is relevant to many careers	Administered survey to states receiving School-to-Work federal grants to identify unit topics embedded in career areas of possible interest to learners, with potential to address reforms-aligned science, having demand for work-based science curriculum; Reviewed content standards from science frameworks	Reviewed occupational information (pre-requisite knowledge, qualification, nationwide prevalence); Matched selected occupations with science standards to choose unit topics and occupations; Chose narrow set of standards to treat science content deeply	External appraisal of science standards' coverage; recommended fewer standards with more depth, revisiting standards across units
EE (a) Workplace-inspired, hands-on design-and-build projects; learners build prototype devices to explore, apply concepts, practice engineering design process (b) Minimal reading load to encourage active exploration of concepts, avoid disconnected reading assignments (c) Learners visit relevant workplaces, interact with professionals to reach beyond the classroom, see science applied on the job	Reviewed other science curricula to identify compatible pedagogical approaches in preparing grant proposal; formulated initial vision of design-and-build projects	Compared strengths and limitations of learning activities of other science and math curricula vis à vis own aims, target audience; prioritized learner experiences, teacher practices for present curriculum; refined initial vision	Classroom testing data used to determine optimal timing in curriculum for workplace visits, make workplace visits more salient

(d) Teachers as facilitators; elicit learners' ideas, engage them with questions and discussions			
WC			
(a) Science situated in broad range of potentially appealing career contexts; unit projects inspired by tasks and problems of various careers in engineering, technology	No data available	Reviewed written materials of other science, mathematics curricula to generate detailed specifications for level of support, format of learner, teacher materials; noted lack of connections between activities and context in other materials; emphasized workplace-inspired storylines and scenarios in present materials	External appraisal suggested making workplace storylines more salient, using workplace contexts not only to engage learners' interests, but also to understand underlying scientific concepts and technical practices
(b) Storylines in learner resource book present workplace-inspired unit projects, contextualize activities and content in workplace scenarios			
(c) Ongoing work records in job sheets, stepwise instructions, and just-in-time background information via readings in learner resource book			Classroom testing data used to revise work-based unit projects, design workplace inspired problems with potential for rich connections to science
(d) Questions and instructions in job sheets and learner resource book to guide learners' interactions with workplace professionals		Designers visited actual work sites to identify workplace praxis to guide supports for design projects	Classroom testing data used to revise instructional activities to address difficult content
(e) Guidelines to teachers for using scientific language, instructional strategies, information on learners' understanding		Unit project activities tested internally by curriculum's designers to ensure sufficient complexity, applications of scientific knowledge	

Legend: CM = Curriculum Manifestations; DP = Design Processes; IO = Intended Outcomes; EE = Envisioned Enactment; WC = Written Curriculum

2.7.1 IO

The designers wanted learners to comprehend and integrate a limited set of key physics concepts (related to kinematics, forces and motion, electricity and magnetism, and energy), and engineering design practices such as generating questions, designing and building solutions to specifications, gathering and analyzing appropriate data from investigations, and communicating ideas orally and in writing. Further, the designers wanted learners to demonstrate these understandings via rich performances where they would apply relevant physics concepts and practices to solve design projects. By connecting physics with work in engineering and technology, the designers hoped ultimately that learners would understand how scientific knowledge was integral to many careers. As curriculum writer P5 and project leader P1 described respectively, they wanted learners to appreciate "science as something that's actually relevant to various kinds of work," and to "be able to extract from a work site visit or an activity, the scientific concepts that were relevant to their learning."

2.7.2 Design process to develop IO

To situate the curriculum in career areas that would appeal to a broad range of learners, and to select a broad career cluster (career path or major) with (a) potential for teaching standards-based science, and (b) significant demand for work-based science curriculum, in the analysis phase, the designers surveyed the 26 states in the U.S. receiving federal School-to-Work (STW) grants, as well as subscribers to the STW Net listserv. Through this survey, they identified Industrial and Engineering Technology (IET) as a career cluster with ample scope to address rigorous science, and for which all respondents in their survey were offering courses. This cluster included the fields of engineering, maintenance and repair, and industrial technologies, and pointed designers to potential unit topics related to these fields. In addition to surveying career areas, the designers also examined a wide range of content standards from national and state science frameworks to identify rigorous content that was recommended.

The designers' activities during development and evaluation phases yielded insights about content and learning goals. Early in the process, to choose unit topics and represent suitable occupations in the curriculum, the designers conducted a job market study of over 50 occupations in the IET career cluster. They reviewed occupational information from the *Occupational Outlook Handbook* published by the Bureau of Labor Statistics (within the U.S. Department of Labor), and distilled key aspects like knowledge and qualification for entering the field and nationwide prevalence of the occupations. The designers also matched selected occupations with the science standards, focusing on science and technology knowledge among others. This measure helped them specify that occupations included in the curriculum should address substantive scientific content, and be comprehensible, attractive, and accessible to target learners.

Furthermore, the designers got advice from the funding agency's program officer, who examined a chart of science standards covered in each unit. He recommended addressing fewer standards in more depth, and revisiting those standards throughout the full year course, instead of addressing them only once. In developing the units, therefore, the designers chose a narrow set of standards to ensure deeper treatment of the content. As project leader P1 explained, "in each framework document, or standards document, we did not address all of the standards, because it would be impossible, we thought, to have any kind of meaningful learning."

2.7.3 EE

The designers imagined each curricular unit would center on a long-term, hands-on design-and-build project lasting approximately six weeks, and involve activities related to designing, building and evaluating devices. Workplaces were used to contextualize these unit projects in the curriculum, meaning that learners' projects were inspired by authentic workplace-related problems and scenarios, and introduced scientific concepts and technical practices used in workplaces to solve those problems. As written in a progress report, the designers wanted to "situate science learning in authentic workplace-related problems that are likely to capture students' interest, and that highlight the relevance of physics to their lives and potential future livelihoods." For example, in a unit on electricity and simple circuits, the project is to design, build, and test an electric circuit akin to a circuit controlling a defibrillator used in hospitals. The model defibrillator circuit project is thus situated in the field of biomedical equipment maintenance in hospitals, where technicians conduct critical maintenance and repairs on medical and related technical equipment, and need to understand scientific concepts related to electricity such as charge, voltage, and resistance.

Design-and-build projects (a form of project-based learning) were stressed so that learners would investigate and apply relevant physics concepts actively to solve practical problems, while also practicing engineering design skills such as measurement and analysis to construct devices, using specific metrics to test performance of the devices, and iteratively revising the devices. As curriculum writer P5 expressed, the designers aimed to foster "the kinds of understanding that come from actually working with, engaging with the ideas rather than just, you know, being exposed to the ideas so that the hands on and project-based stuff is important." Indeed, building devices such as prototypes of motion toys and defibrillator circuits was symbolic of this curriculum's pedagogy, as indicated by curriculum writer P4:

> *This particular unit [on energy], and each unit in the [student resource] book, is designed to have students do science, not read about science. And it took the approach that kids would be acting like scientists, using the tools of scientists or technicians, and actually making something, building something, constructing something using engineering skills along the way.*

Further, the designers intended to keep a minimal reading load because they wanted learners to explore scientific concepts actively through the unit projects, instead of simply reading about the concepts. As project leader P1 stated, they wanted to avoid teaching science as a "series of disconnected reading assignments." Curriculum writer P4 also expressed this vision in the interviews: "So that's our vision, that kids are learning, uncovering information for themselves, and not reading about it, not— We hate the idea of giving away the answer before they even have a chance to look at the concept."

The designers envisioned also reaching beyond classroom simulations of work-based projects to expose all learners to real world models and applications of scientific knowledge in actual workplaces. They imagined incorporating relevant work site visits and learners' interactions with professionals. These visits were intended to help learners 'see science in action' – to reinforce and enhance their understanding of how scientific concepts and technical practices introduced in the classroom were used to tackle problems in various occupational fields - and to learn about careers where science was a key component of workplace praxis.

Finally, the designers believed teachers were crucial in supporting learners with this curriculum, and they wanted teachers to guide learners in particular ways. Project leader P1 recalled that they wanted teachers to "elicit student ideas, to recognize that there's not necessarily one right answer; that a quote-unquote wrong answer can lead to further exploration and understanding." The designers imagined teachers would pose questions to help learners explore ideas and reflect on outcomes of their unit projects. Further, according to internal formative evaluator P6, their envisioned enactment emphasized classroom discussions, and the designers wanted the discussions to be "one of the central experiences that kids have, which is reflecting and then pushing their understanding through discussion."

2.7.4 Design process to develop EE

In the analysis phase, the designers reviewed other science curricula to identify compatible pedagogical approaches, and to consider adopting or adapting suitable portions. In fact, they took this step before the curriculum was funded to formulate their initial vision for enactment in the grant proposal. This excerpt from the grant proposal shows the designers were inspired by a design-and-build project approach of another science curriculum developed previously at the designers' organization.

> *[In-house] curriculum has established an approach for motivating science concept learning through design-and-build challenges. We intend to use this approach within several … [present curriculum] units…. [In-house curriculum] is developing units — Simple Machines and Energy Audits — which are substantively related to the … [present curriculum's] areas of study. Supporting each of these design-and-build units are a collection of mini-challenges and mini-lessons that help students develop the conceptual understandings and manual skills they will need to solve the larger challenge.*

After receiving the grant, in the development phase, the designers continued to review existing science and mathematics curricula to learn from other approaches, and to refine their own vision for enactment. The team discussed strengths and limitations of different activities addressing content in those curricula, keeping in mind their own curriculum's aims and target audience. The designers noted various learning activities in this review: inquiry learning, data collection and writing, teacher-led discussions that solicited learners' ideas and engaged their interests, and project-based assessments that explicitly connected the science content to the assessments. Learners designed their own experiments in some activities, whereas other activities did not allow learners to design or share their experimental methods, were too prescriptive and not sufficiently investigatory. The review helped designers prioritize how they wanted to improve learners' experiences and teachers' practices. For example, they stressed project and performance-based assessments of learners' mastery of scientific concepts and skills, inquiry and applied learning, focusing on learners' interests, and teachers guiding learners to construct their own understandings of the concepts and skills, instead of providing answers to learners.

In the evaluation phase, the designers' vision for enacting workplace visits was refined iteratively through pilot testing in classrooms. Specifically, after they noted that learners valued the real-world nature of workplace visits, the designers decided to enact workplace visits earlier instead of later in the unit activities. This choice aimed to make the workplace connections more salient in the curriculum.

2.7.5 WC

Consistent with the designers' vision, the unit projects were inspired by tasks and problem-solving practices drawn from various engineering and technological careers of potential interest to learners (see Table 2.6).

Table 2.6: Curriculum units, projects and relevant career contexts.

Curriculum Unit	Unit Project	Career Contexts
Kinematics	Construct and test a Creepy Crawly motion toy and compare it to other toys on the marketplace	Mechanical and design engineering
Forces and Motion	Designing, planning, and implementing a performance test for All Terrain Vehicle tires for different conditions and types of motion	Mechanical and design engineering
Electricity and Simple Circuits	Design and build an electric circuit similar to the circuit controlling defibrillators used in hospitals.	Clinical engineering, medical equipment maintenance
Generators and Diodes	Modify the circuitry of a generator-powered bicycle light to improve its function	Automotive electrical technology and repair
Energy	Build, test, and operate components of a working radio station to transmit notes from an instrument	Sound system engineering, Audio equipment design

To evoke the workplace context in unit projects, there was a workplace-based storyline in the learner resource book, explicating how learners would perform the roles of engineers, designers or technicians throughout the unit. The projects were written in the learner book and teacher guide as sequences of milestones. The milestones modeled phases of the engineering design process, leading learners from the initial problem to a final solution. The milestone tasks were embedded performance tasks, asking learners to demonstrate their understandings by applying relevant physics concepts and engineering practices to design, build, and test devices. Further, the activities built on one another and introduced content on a 'need to know' basis, making certain concepts and practices prerequisites to attaining the milestone performances, and ultimately, the overall unit project.

The storyline contextualized learning activities and science content of unit project milestones in workplace-related scenarios, and flowed throughout a unit to tie the milestones and activities with relevant work contexts. The overarching storyline in the kinematics unit, for example, presents learners' roles as engineers working for a fictitious toy design company, and the unit project is to design, build, and test the performance of a Creepy Crawly motion toy, and to compare it to competitor toys in the marketplace. From the preliminary design to the final testing and comparative analyses of different toys, learners simulate the work of engineers in their classrooms. Table 2.7 shows how the project milestones in the Kinematic unit are contextualized in workplace-related scenarios, and model the engineering design process.

Table 2.7: Mapping of project milestones to workplace scenarios and the engineering design process.

Project milestone	**Workplace-related scenario**	**Phases of Engineering Design Process**
Prepare a feasibility report of a Creepy Crawly motion toy, describing its performance, testing methods used, and suggestions for improvement.	The toy company's marketing team gives a work order with specifications and performance measures to construct and test a prototype toy. After initial testing, learners modify one characteristic of the prototype to improve its performance, and test the modified toy. Learners prepare a feasibility report for the marketing team.	Build solution conforming to design constraints; evaluate and redesign; communicate the solution
Prepare a comparative analysis report comparing the prototype toy to an ideal toy, and to the competitor's top toy.	Marketing team gathers specifications of an ideal motion toy from focus groups of typical consumers. Learners compare performance measures of their prototype toy to these specifications of the ideal toy. They also compare the performance of their prototype to the specifications for the competitor's top toy already on the market. Based on comparisons of their prototype toy to the ideal toy and the competitor toy, learners prepare a comparative analysis report for the marketing team, recommending whether the company should develop the Creepy Crawly motion toy.	Evaluate possible solutions; communicate
Prepare report reviewing the rest of the toy company's product line, including	Based on the series of performance tests conducted before, the marketing team asks learners to test working models of other toys from the company that are market-ready. Marketing team also provides learners with	Evaluate possible solutions; communicate

comparisons to the products' top competitors.	motion graphs of the competitor toys. Learners create motion graphs for their company's toys, and compare these to the graphs of the competitor toys. Learners prepare a report of their analyses of specified performance measures for the marketing team.

To guide learners through each activity of a unit project, there were activity sheets called 'job sheets'. The job sheets were consumable black-line master work records, containing procedures, design specifications and data, and questions to help learners reflect on scientific concepts behind the activities. Learners used job sheets to write their ideas and questions, record data after testing their designs, and to use representations like diagrams and graphs. The job sheets contained stepwise instructions for design and experiments, and were separate from the learner resource book, a non-consumable material.

Additionally, the learner book contained stepwise instructions for activities, and background information on physics concepts and technical practices was presented just-in-time via required readings. As described in a progress report, the book was designed as a resource guide for learners to periodically refer to during their unit projects, much like technical manuals used on the job, and unlike traditional textbooks. There was a reading tied to almost each activity, explaining scientific and technical terminology needed to perform the milestones. In fact, the readings were intended as 'concept builder' activities to help learners step back from design and experimentation, and focus on physics concepts and technical processes emerging in the course of their unit projects. Moreover, to avoid disconnected reading assignments as envisioned by the designers, the readings were assigned in the written instructions as required steps for completing the activities, thus making them purposeful to the unit projects. Their integration with milestone activities meant that relevant information had to be applied to complete the projects.

To illustrate, a milestone performance in the unit on electricity and simple circuits presented earlier asks learners to determine a safe level of current for the model defibrillator circuit, and to measure voltage and resistance in the model. To help learners understand and measure current, voltage and resistance in performing activities for this milestone, the readings introduce information on how current moves in a circuit, on voltage, conductivity and resistance, and on Ohm's law.

Additionally, there were supports to enact workplace visits. At least one milestone activity in each unit project required learners to visit a relevant work site (or, if that was not possible, teachers could arrange classroom visits by workplace professionals). Curriculum writer P4 described the worksite visit in a unit on energy, where the project is to build a model of a working radio station with a transmitter and receiver:

> *So there might be a trip to, in this unit, there's a trip to an audio specialist, where they visit someone either on their own or with their class, and ask them questions about science principles as applied to the workplace.*

To guide learners' interactions with professionals, the job sheets contained questions on the functioning of physical devices related to the unit projects; on physics concepts and technical processes used on the job that related to the projects; and on the nature of tasks performed in those career settings. These questions were given to teachers, learners and workplace professionals prior to worksite visits. The learner resource book also asked learners to review and discuss the questions in class, and to raise these during work visits.

Finally, aligned with the designers' vision for enacting the curriculum, the teacher guide contained supports to implement the design-and-build projects. For each milestone of a unit project, lesson-embedded text indicated when and how to introduce relevant scientific terms and conceptual information in the course of an activity, drew teachers' attention to learners' possible understanding of and difficulties with particular concepts and practices, and suggested ways to address those. These conceptual notes were separated from other lesson-specific teaching strategies. There were stepwise questions to lead whole class discussions and help learners step back from experimentation and design work and reflect on scientific principles underlying their work. Some questions elicited learners' initial understandings to lead into particular activities, others prompted interpretations of data collected during experiments, and yet others probed learners' reasoning about concepts arising during the course of the projects. The teacher-led discussions were thus crafted as complementary support to help learners make scientific meaning of their design and construction activities.

2.7.6 Design process to develop WC

In the development phase, to determine appropriate levels of support and format of written materials for the present curriculum, the designers examined strengths and limitations of other written curriculum materials. They analyzed teacher materials to determine how best to support teachers in responding to learners' thinking and in facilitating scientific practices, noting that some teacher materials explicated what teachers should say during instruction and separated it from conceptual notes, which helped streamline the text. On the other hand, some materials offered little support to teachers about possible learner responses, and ways to facilitate data collection and interpretation. Based on these insights, the designers specified providing text for teacher talk and separate conceptual notes, and recommendations in the teacher guide for the present curriculum to help learners draw conclusions from hands-on investigations and construct their own understandings of the scientific concepts and practices.

Additionally, the designers examined learner materials to determine how best to support learners to conduct and reflect on the results of their experiments, noting that some curricula did not adequately motivate learners with a need to know particular content, and there was little guidance for learners to produce written reflections about their experiments. Therefore, for learner materials in the present curriculum, the designers specified producing a non-consumable student book containing descriptions of activities, and references to worksheets where learners could record their thinking.

The designers found also that although some curricula presented learners' activities in real world contexts, the materials did not always contain clear storylines to connect the activities and context explicitly. Therefore, in specifying their written materials, the designers emphasized that in the learner resource book, each unit would present a storyline that approached scientific concepts through the lens of a work challenge that may be addressed by professionals in various workplaces, and that the storyline would flow throughout a unit and link the activities together. The designers specified that each unit would include workplace scenarios to portray authentic situations where science concepts were applied and introduce problems that learners must solve.

To embed unit projects in suitable work contexts, the designers visited different workplaces and interviewed professionals like automotive alternator specialists, battery engineers, studio lighting designers, and light manufacturers. The purpose of these visits was to learn about actual workplace problems, processes, and science used on the job, and to guide the designers' choice of unit projects and milestone activities. The insights from these visits were critical to help designers "see the world through the eyes of technicians," and to ensure that the content, storylines, and flow of project activities were contextualized in real workplace praxis.

A key challenge in structuring the units was integrating the unit project and milestones with the target science content. Specifically, the milestones had to be sequenced logically as steps leading learners from the initial problem to a final solution, helping learners complete the project. But it was also crucial to equip learners with the necessary scientific understanding to develop the final solution. Thus, the milestones had to address target scientific concepts and skills in a meaningful sequence. Therefore, to generate suitable unit projects, the designers themselves tested the unit activities conceptually, examining whether the unit projects would engage learners over several weeks, were sufficiently complex, and would require learners to apply target scientific content to complete the projects.

In the evaluation phase, there were two main sources of feedback to help the designers strengthen workplace connections and learners' understandings in the curriculum units. First, the funding agency's program officer drew the designers' attention to their target learner audience, with implications that workplace examples at the beginning of the curriculum units should not simply serve to elicit the learners' interests or provide an indirect way to understand science. Rather, the units should help the learners understand what technicians and engineers actually do related to the unit content and activities. Based on this feedback, therefore, the first project leader emphasized making workplace storylines more salient in the units so that learners would better understand how technical tasks were performed in certain work settings, and what scientific ideas were involved.

Second, the designers used data from classroom testing to choose workplace-inspired problems with potential to connect to scientific understandings in the unit projects. See this excerpt from a progress report:

> *We substantially modified the original Forces and Motion unit. The core project— analysis of actual bicycle accident reports— met with limited success.*

> *The pilot revealed that workplace supervisors did not adequately relate their work to scientific understandings or technological processes. Hence, we developed a new core project— design and implementation of a tire performance test. The field test indicates that the design engineers working with students in this project are indeed making the important connections between science and work.*

Based on classroom testing, the designers also generated activities to address challenging content. For example, the pilot test of a unit on kinematics revealed learners' difficulties with graphical representation. These skills were critical in accomplishing the unit's project of building a prototype motion toy, and generating and interpreting graphical representations of its performance data. Hence, the designers rewrote the materials to include additional activities with graphing motion detectors to help learners produce and interpret graphs.

Based on how the designers steered their design process, and the insights they generated in developing a work-based science curriculum to promote deep understanding and rich performance in learners with different aspirations, the following section discusses implications of this work to guide other designers seeking to develop science curricula with similar goals.

2.8 Discussion

2.8.1 Guidelines for work-based curriculum design

This study presents a worked example of one high school physics curriculum which, through its work-based approach, aimed to promote deep understanding and rich performance in learners with diverse aspirations. The results show how designers generated learning experiences that are authentic, appealing, and rigorous for learners. It reveals their decisions and rationales. The answers to the research question about curriculum manifestations and design processes were summarized in Table 2.5. Based on these findings and in light of relevant literature, this section offers four key guidelines for the design of work-based curricula aiming to serve learners with varied inclinations. In addition to designers, the guidelines can also be useful to teachers wishing to adapt curriculum materials and customize experiences for their learners (Barab & Luehmann, 2003; Squire et al., 2003). After summarizing the four guidelines and the key findings from which these were derived in Table 2.8, each guideline is elaborated.

Table 2.8: Product and process guidelines for work-based curriculum distilled from this example.

Guidelines for product/process	Based on product findings	Based on process findings
(i) Select for synergy. Ensure content is core to both the science discipline and workplace contexts	Students' learning focuses on applying standards-based key physics concepts and engineering design processes to solve design projects, and	Surveyed states to identify unit topics within potentially appealing career areas, with scope to address rich science, and

	understanding relevance of science to many careers	in demand for work-based science curriculum; Selected content standards from science frameworks Reviewed occupational information, matched selected occupations with science standards to choose unit topics and occupations Designers visited work sites to learn about workplace praxis
(ii) Align manifestations. Integrate the workplace context across IO, EE and WC	Learning goals emphasize key standards-based physics concepts and engineering design processes that are integral to many work settings Curriculum enactment stresses on workplace-inspired, design projects in classrooms, coupled with learners' visits to relevant workplaces Written materials (work-based storylines and scenarios, job sheets, and supports for worksite visits) convey workplace connections explicitly and throughout units	Reviewed learner materials of other curricula
(iii) Provide specific teaching strategies and information on learners' understanding. Anticipate and attend to learning needs for the enactment of work-based science instruction	Curriculum envisions teacher facilitation in the form of eliciting learners' ideas, engaging learners with questions and discussions Guidelines for using scientific language, content, and instructional strategies, and for anticipating and addressing learners' alternative understandings	Reviewed teacher materials of other curricula

(iv) Prioritize evaluation concerns. Focus on reforms-aligned content, instructional supports, science and workplace connections, and timing of learners' workplace visits	Not applicable	External appraisal of content coverage, work contexts represented in written materials Internal testing of unit activities by designers to assess content coverage Classroom testing to revise instructional supports, select work-inspired unit projects with strong connections to science used on the job, identify appropriate timing of learners' workplace visits

Legend: IO = Intended Outcomes; EE = Envisioned Enactment; WC = Written Curriculum

2.8.1.1 Select for synergy

To equip all learners with fundamental scientific knowledge, a science curriculum needs to address rigorous content, emphasizing core understandings of the target scientific discipline. Local and national frameworks of science educational policies will point designers to key concepts of a discipline. To allow learners ample opportunities to investigate key ideas deeply and engage in the work of engineers and technicians, however, formulating a limited set of intended learning outcomes is recommended. Focusing on limited core science ideas instead of covering broad content is consistent with reform frameworks (e.g., NRC, 2012). Furthermore, aligning the intended outcomes with science that is core to different work settings of interest to the majority of learners will contextualize the science in authentic, appealing, and rigorous contexts. This contextualization will help learners recognize how science is relevant to many careers that appeal to their inclinations, thus making science learning meaningful, as recommended by educators (Marginson et al., 2013; Osborne & Dillon, 2008). Hence, it is worthwhile to take the time to explore and identify the content areas that align with both the discipline and the work context.

Based on the design process found in this study, three strategies are proposed to help designers identify science content that is rigorous as well as core to appealing workplaces. One strategy in the analysis phase is to gain insights into the needs of schools that wish to teach science from a career perspective. Specifically, designers may consider administering a needs assessment survey (McKenney & Reeves, 2012; Edelson, 2002) in secondary schools that (wish to) offer courses related to career areas of potential interest to learners with diverse inclinations. The data from such needs assessment can point designers to suitable work-based science content topics.

Next, in developing curriculum units, it is useful to compare content emphasized in science educational policy frameworks with the background science and technology knowledge needed in target careers. This requires designers to review thoroughly both policy documents from local and/or national levels (Krajcik et al., 2008; Rivet & Krajcik, 2004; Songer, 2006), as well as pertinent literature on different jobs in target career areas. In so doing, designers can generate specifications for including suitable career contexts in the curriculum.

Another measure in the development phase, which was salient in this study, is designers' visits to relevant workplaces. Interacting with engineers and technicians can give designers feedback on actual problems, processes, and science used on the job. This strategy for learning about science used on the job is comparable to the design processes of other science curricula. Specifically, designers of other reform-based science curricula seek input from scientists to learn about their authentic practices (Edelson et al., 1999), and to determine important scientific facts in science content areas (e.g., Songer, 2006). The resultant insights from workplace visits can guide designers in choosing suitable problems that address important science content. Likewise, designers can ensure that the intended science content is integral to the kinds of careers that learners may consider after secondary school. Taking concrete steps to learn about different science-based work settings is crucial especially if designers lack adequate knowledge about work contexts that are appealing to learners with different inclinations, and that would also lend themselves well to teaching reforms-based science.

2.8.1.2 Align manifestations

To make reforms-based science appealing to learners with different inclinations, it is important to contextualize scientific concepts in problems and practices of actual work settings that are of potential interest to the learners. In so doing, it is recommended that designers use the workplace context across curriculum manifestations, planning intended learning outcomes and content, enactment of activities, and written materials that situate and organize target science content around workplace challenges. Using the workplace context consistently across curriculum manifestations will help align designers' ideals and written materials (McKenney et al., 2006), and strengthen the desired connections between reforms-based science and workplaces.

Specifically, learning goals derived from curriculum frameworks should be aligned with science that is integral to real work contexts that designers wish to represent. This is critical to help learners understand how scientific concepts and practices are necessary to solve practical problems in workplaces. Further, in envisioning enactment of design projects to contextualize scientific knowledge, the projects should be based on key problems from a broad range of work settings of potential interest to the learners. The design projects should simulate different phases of real work praxis, leading learners from the initial problem to a final solution, and helping them see how they are working like engineers and technicians. As suggested in reform documents (Marginson et al., 2013; NRC, 2012, 2013), engineering tasks and activities can promote problem-solving and applications to real world contexts, and therefore need to be designed well to engage learners. Additionally, interacting with professionals using science in action can help learners appreciate connections between curriculum science and possible careers, also a key recommendation (Marginson et al., 2013).

Finally, it is recommended that written materials convey workplace connections *explicitly* and *throughout* unit activities to help learners understand how science relates to their potential careers and livelihoods. The storylines and work scenarios presenting learners' hands-on design projects in the learner materials of this curriculum, the job sheets guiding their' investigations, and supports for workplace visits are examples of how text and language in a curriculum can be designed to evoke workplaces and to situate learners' experiences in concrete and authentic contexts. Thus, instead of simply presenting design projects as 'workplace inspired challenges' at the beginning of curriculum units to merely elicit learners' interests, the written materials need to reinforce connections between reforms-based science and career contexts throughout different instructional activities. A detailed review of other curricula can shed light on what kinds of supports may be required to evoke workplaces in the written curriculum.

2.8.1.3 Provide specific teaching strategies and information on learners' understanding

In developing a work-based curriculum, supporting teachers to enact work-inspired design projects merits special attention. This is because simulating workplace problems and processes, and connecting these to underlying scientific principles can be as unfamiliar to teachers as to the learners. Indeed, previous research suggests that science teachers may not always be familiar with enacting scientific practices (Knight-Bardsley & McNeill, 2016; Krajcik & Blumenfeld, 2006; Simon et al., 2006) or engineering design process (Mehalik et al., 2008), and may even hold misconceptions about authentic practices (Zangori et al., 2013). To simulate engineering design projects in the classroom, therefore, the authors recommend designing materials to include procedural supports (Pareja Roblin et al., 2018) as well as educative elements to facilitate teachers' enactment of the curriculum (Bismack et al., 2015; Davis et al., 2014; Davis & Krajcik, 2005).

As manifested in this science curriculum, teacher materials may provide procedural supports to implement whole class discussions, like stepwise questions for eliciting and probing learners' understandings of scientific concepts and tips on appropriate presentation of scientific language and content. Additionally, this worked example shows how teacher guides may include educative supports to foster teachers' knowledge for teaching target science topics (Davis & Krajcik, 2005). To this end, based on the present curriculum, the authors recommend embedding information to anticipate learners' possible (alternative) understanding or difficulties in the subject, and suggestions for addressing these. These kinds of supports may help teachers implement key instructional activities stressed by educators, for example, performance tasks, open-ended questions, and discussions (NRC, 2015; Tytler, 2007). These kinds of supports have been shown to have positive impact on learner outcomes (Pareja Roblin et al., 2018). Here, too, a review of other curricula can generate insights into crafting appropriate materials for teachers.

2.8.1.4 Prioritize evaluation concerns

In evaluating and iteratively refining a work-based science curriculum, designers are advised to focus on the following four areas distilled from the worked example presented in this study: coverage of (reforms-aligned) content; adequacy of instructional supports; connections between science and workplace significance; and timing of learners' workplace visits. Whereas the first two areas are common to good curriculum design, the last two are specific to fostering workplace connections in a work-based science curriculum. Together they address curriculum manifestations (IO, EE, WC) and contextualization of science in work settings.

Additionally, designers may utilize different evaluation strategies to develop insights into these areas. For instance, external appraisal from experts (Krajcik et al., 2008; Thijs & van den Akker, 2009) may shed light on the range of (reforms-aligned) science content that should be addressed. Further, designers may themselves conceptually test hands-on design projects and their associated activities to assess target content coverage (Kanter, 2010), and to integrate target science learning goals within the structure and performance tasks of the design projects. This strategy may help ensure that unit project tasks are sufficiently complex and require learners to apply intended science content to solve problems. Also, testing the curriculum units with learners (Branch & Merrill, 2012; Gustafson & Branch, 2002) may reveal their difficulties with particular concepts and skills, and point to revisions in instructional supports.

With respect to workplace significance of the science content, pilot and field tests may indicate how well problems and processes simulated in the hands-on design projects connect to science used on the job, thereby guiding designers to select suitable work-based design projects with rich science content. Finally, classroom testing may yield insights into appropriate timing for enacting workplace visits during instructional activities.

2.8.2 Reflections and recommendations

This research used a case study approach involving interviews and curriculum project documents, in which documentation prepared by the researchers was shared with the participants before the interviews. But the retrospective nature of the study necessitated participants to rely on their memories, particularly of the design processes, making it difficult at times to provide details of particular measures they took and/or insights they gained in creating and revising the curriculum manifestations. To address this limitation, the researchers extracted relevant information, wherever available, from project documents to confirm and extend the interview data, and to obtain new information. Although using multiple data sources yielded rich information, some phases of the design process for particular curriculum manifestations were not mentioned in sufficient detail in the interviews or project documents. As a result, these phases were not analyzed in depth or were excluded from the data analyses and findings. In the future, it could therefore be beneficial to study curriculum projects that are in progress. This may allow researchers to analyze products and design processes in more detail, and without needing to rely on participants' recall of information. To study curricula in progress, researchers may consider gathering data through observations of the unfolding curriculum design process, in addition to analyzing drafts and prototypes of curriculum documents, and conducting interviews with designers to gather their insights on emerging design challenges and strategies.

Further, this study reveals the meticulous and time-consuming work that is involved in developing a science curriculum product that can yield positive learning outcomes. Indeed, high quality curriculum design is a costly effort which requires considerable and continued funding (Burkhardt & Schoenfeld, 2003). Further research on the outcomes of this process could help designers and policymakers alike. For designers, it would be useful to know: Do all the features of the written curriculum as described here contribute to positive outcomes? Equally? Or are particular curriculum features more regularly associated with positive learner outcomes? For policymakers, broader analysis of funded curriculum design projects and their outcomes could give important feedback on past funding support, and help identify key concerns to be taken up in future programs that support curriculum design.

2.9 Conclusion

By presenting a worked example of a high school physics curriculum which aimed to promote deep understanding and rich performance in learners with diverse aspirations through its work-based approach, this study is germane to international policy recommendations. It stands to support policy implementation indirectly, by offering insights to researchers, teachers and other science educators who engage in curriculum design. Designing this kind of contextualized science curriculum is difficult, especially if designers are not familiar with ever-changing science and technology-based careers. The findings of this study can help designers think through and critique the intended outcomes, their vision for enactment and features of the written curriculum, as well as the processes through which each of these are created. The guidelines derived from this study can help designers to focus on hands-on design projects that address a limited set of key reforms-aligned learning goals, contextualized in authentic work-inspired practices that are appealing to learners with a broad range of interests. Altogether, this study offers modest but crucial insights for designers creating curricula with workplace connections that can make science engaging and relevant to all learners.

References

Barab, S. A., & Luehmann, A. L. (2003). Building sustainable science curriculum: Acknowledging and accommodating local adaptation. *Science Education, 87*, 454–467.

Bismack, A. S., Arias, A. M., Davis, E. A., & Palincsar, A. S. (2015). Examining student work for evidence of teacher uptake of educative curriculum materials. *Journal of Research in Science Teaching*, *52*(6), 816–846.

Branch, R. M., & Merrill, M. D. (2012). Characteristics of instructional design models. In *Trends and Issues in Instructional Design and Technology (3rd edition)* (3rd ed., pp. 8–16). Boston, MA: Pearson.

Burkhardt, H., & Schoenfeld, A. (2003). Improving educational research: Toward a more useful, more influential, and better-funded enterprise. *Educational Researcher*, *32*(9), 3–14.

Clarke, J., & Dede, C. (2009). Design for scalability : A case study of the River City curriculum. *Journal of Science Education and Technology*, *18*, 353–365.

Davis, E. A., Janssen, F. J. J., & Van Driel, J. H. (2016). Teachers and science curriculum materials: Where we are and where we need to do. *Studies in Science Education*, *52*(2), 127–160. https://doi.org/https://doi.org/10.1080/03057267.2016.1161701

Davis, E. A., & Krajcik, J. S. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher*, *34*(3), 3–14.

Davis, E. A., Palincsar, A. S., Arias, A. M., Bismack, A. S., Marulis, A. M., & Iwashyna, S. K. (2014). Designing educative curriculum materials: A theoretically and empirically driven process. *Harvard Educational Review*, *84*(1), 24–53.

Duschl, R. A., Schweingruber, S. A., & Shouse, A. W. (2007). *Taking science to school: Learning and teaching science in grades K-8*. National Aacdemies Press.

Edelson, D. C. (2002). Design research: What we learn when we engage in design. *Journal of the Learning Sciences*, *11*(1), 105–121. h

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences*, *8*(3–4), 391–450.

Edelson, D. C., & Reiser, B. J. (2006). Making authentic practices accessible to learners: Design challenges and strategies. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 335–354). New York: Cambridge University Press.

Ertmer, P. A., & Quinn, J. (2007). *The ID case book: Case studies in instructional design (3rd edition)*. New Jersey: Pearson.

Goldberger, S., & Kazis, R. (1996). Revitalizing high schools: What the school-to-career movement can contribute. *Phi Delta Kappan*, *77*(8), 547–552.

Goodlad, J., Klein, M., & Tye, K. (1979). The domains of curriculum and their study. In J. Goodlad & Associates (Eds.), *Curriculum inquiry: The study of curriculum practice* (pp. 43–76). New York: McGraw-Hill.

Gustafson, K. L., & Branch, R. (2002). *Survey of instructional design models (4th edition)*. Syracuse University: ERIC Clearninghouse on Information Resources.

Howard, C. D. (2013). The rhetoric of Instructional Design Cases: Knowledge building via examples of process and product. In B. Hokanson & A. Gibbons (Eds.), *Design in educational technology: Design thinking, design process, and the design studio* (pp. 107–124). Springer Press. https://doi.org/10.1007/978-3-319-00927-6

Howard, C. D., Boling, E., Rowland, G., & Smith, K. M. (2012). Instructional design cases and why we need them. *Educational Technology*, *52*(3), 34.

Kanter, D. E. (2010). Doing the project and learning the content: Designing project-based science curricula for meaningful understanding. *Science Education*, *94*(3), 525–551. https://doi.org/https://doi.org/10.1002/sce.20381

Kena, G., Hussar, W., McFarland, J., de Brey, C., Musu-Gillette, L., Wang, X., & Dunlop, Velez, E. (2016). The condition of education 2016. May 2016. Retrieved from http://nces.ed.gov/programs/coe/indicator_cpa.asp

Kennedy, J. P., Lyons, T., & Quinn, F. (2014). The continuing decline of science and mathematics enrolments in Australian high schools. *Teaching Science*, *60*(2), 34–46.

Knight-Bardsley, A., & McNeill, K. L. (2016). Teachers' pedagogical design capacity for scientific argumentation. *Science Education*, *100*(4), 645–672. https://doi.org/https://doi.org/10.1002/sce.21222

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gary, J., Holbrook, J., & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle school science classroom: Putting learning by design into practice. *Journal of the Learning Sciences*, *12*(4), 495–547. https://doi.org/https://doi.org/10.1207/S15327809JLS1204

Krajcik, J. S., & Blumenfeld, P. C. (2006). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 317–333). New York: Cambridge University Press.

Krajcik, J. S., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education*, *92*(1), 1–32. https://doi.org/https://doi.org/10.1002/sce.20240

Lee, H. S., & Butler, N. (2003). Making authentic science accessible to students. *International Journal of Science Education*, *25*(8), 923–948.

Linn, M. C., Clark, D., & Slotta, J. D. (2003). WISE design for knowledge integration. *Science Education*, *87*, 517–538. https://doi.org/https://doi.org/10.1002/sce.10086

Marginson, S., Tytler, R., Freeman, B., & Roberts, K. (2013). *STEM: Country comparisons. Report for the Australian Council of Learned Academies*. Melbourne, Australia.

McKenney, S., Nieveen, N., & van den Akker, J. (2006). Design research from a curriculum perspective. In J. van den Akker, K. Gravemeijer, S. McKenney, & N. Nieveen (Eds.), Educational design research (pp. 67 - 90) London: Routledge.

McKenney, S., & Reeves, T.C. (2012). *Conducting educational design research*. London: Routledge.

McNeill, K. L., & Krajcik, J. S. (2008). Scientific explanations : Characterizing and evaluating the effects of teachers ' instructional practices on student learning. *Journal of Research in Science Teaching*, *45*(1), 53–78.

McNeill, K. L., Lizotte, D. J., Krajcik, J. S., & Marx, R. W. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. *Journal of the Learning Sciences*, *15*(2), 153–191.

Mehalik, M. M., Doppelt, Y., & Schunn, C. D. (2008). Middle-school science through design-based learning versus scripted inquiry : Better overall science concept learning. *Journal of Engineering Education, 97*(January), 71–85.

Merriam, S. B. (1988). *Case study research in education: A qualitative approach*. Jossey-Bass.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative Data Analysis: An expanded sourcebook.* Thousand Oaks, California: Sage.

NGSS Lead States. (2013). *Next Generation Science Standards. Achieve, Inc. on behalf of the twenty-six states and partners that collaborated on the NGSS*. Washington D.C.: National Aacdemies Press. https://doi.org/10.17226/18290

NRC. (1996). *National Science Education Standards*. Washington D.C.: National Research Council.

NRC. (2012). *A framework for K-12 science education: Practices, cross-cutting concepts, and core ideas.* Washington D.C.: National Research Council.

NRC. (2013). *Next generation science standards.* Washington D.C.: National Aacdemies Press.

NRC. (2015). *Guide to implementing the next generation science standards*. National Aacdemies Press.

Osborne, J., & Dillon, J. (2008). *Science education in Europe: Critical Reflections. A report to the Nuffield Foundation*. London.

Pareja Roblin, N., Schunn, C., Bernstein, D., & McKenney, S. (2018). Exploring shifts in the characteristics of US government-funded science curriculum materials and their (unintended) consequences. *Studies in Science Education*, *54*(1), 1-39.

Rivet, A. E., & Krajcik, J. S. (2004). Achieving standards in urban systemic reform : An example of a sixth grade project-based science curriculum. *Journal of Research in Science Teaching*, *41*(7), 669–692.

Sadler, P. M., Coyle, H. P., & Schwartz, M. (2000). Engineering competitions in the middle school classroom: Key elements in developing effective design challenges. *Journal of the Learning Sciences*, *9*(3), 299–327.

Sherin, B., Edelson, D. C., & Brown, M. (2004). On the content of task-structured science curricula. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and nature of science: Implications for teaching, learning, and teacher education* (pp. 221–248). Dordrecht, The Netherlands: Kluwer.

Simon, S., Erduran, S., & Osborne, J. (2006). Learning to teach argumentation: Research and development in the science classroom. *International Journal of Science Education*, *28*(2–3), 235–260.

SjØberg, S., & Schreiner, C. (2005). How do learners in different cultures relate to science and technology? Results and perspectives from the project ROSE. In *Asia Pacific Forum on Science Learning and Teaching, 6*, (pp. 1–16).

Smith, E. (2011). Staying in the science stream: Patterns of participation in A-level science subjects in the UK. *Educational Studies*, *37*(1), 59–71.

Smith, P. L., & Ragan, T. J. (1999). *Instructional Design (3rd edition)* (3rd editio). Hoboken, NJ: Wiley & Sons.

Songer, N. B. (2006). BioKids: An animated conversation on the development of curricular activity structures for inquiry science. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 355–369). New York: Cambridge University Press.

Squire, K. D., McKinster, J. G., Barnett, M., Luehmann, A. L., & Barab, S. (2003). Designed curriculum and local culture: Acknowledging the primacy of classroom culture. *Science Education*, *87*, 468–489.

Symonds, C., Schwartz, R., & Ferguson, R. F. (2011). Pathways to prosperity: Meeting the challenge of preparing young Americans for the 21st century. Pathways to Prosperity Project. Cambridge, MA: Harvard University Graduate School of Education.

Tekkumru-Kisa, M., Stein, M. K., & Schunn, C. D. (2015). A framework for analyzing cognitive demand and content-practices integration: Task analysis guide in science. *Journal of Research in Science Teaching*, *52*(5), 659–685.

Thijs, A., & van den Akker, J. (2009). *Curriculum in development*. Enschede, The Netherlands: SLO Netherlands Institute for Curriculum Development.

Tytler, R. (2007). Re-imagining science education: Engaging students in science for Australia's future. Camberwell: Australian Council for Educational Research (ACER).

van den Akker, J. (2003). Curriculum perspectives: An introduction. In J. Van den Akker, W. Kuiper, & U. Hameyer (Eds.), *Curriculum landscapes and trends* (pp. 1–10). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Van Gog, T., Paas, F., & Merriënboer, J. J. (2004). Process-oriented worked examples: Improving transfer performance through enhanced understandings. *Instructional Science*, *32*(1), 83–98.

Walker, D. F. (1990). *Fundamentals of Curriculum*. San Diego: Harcourt, Brace Jovanovich.

Yin, R. K. (2014). *Case study research: Design and methods* (5th editio). Thousand Oaks, California: Sage Publications, Inc.

Zangori, L., Forbes, C. T., & Biggers, M. (2013). Fostering student sense making in elementary science learning environments: Elementary teachers' use of science curriculum materials to promote explanation construction. *Journal of Research in Science Teaching*, *50*(8), 989–1017.

Chapter 3
Interdisciplinary Teams

Educative curricula support teacher learning as well as the learning of students. High quality educative curricula contain features that help teachers customize learning opportunities and environments in ways that meet the needs of their learners. Designing these features requires expertise related to subject matter content, pedagogy, teacher and student learning, and instructional design. In other words, it requires interdisciplinary teamwork – which is notoriously challenging. To understand and support collaborative interdisciplinary design processes, a retrospective case study was conducted on interdisciplinary design teamwork that yielded a high quality educative curriculum for inquiry-based science learning. Design documents and transcripts of interviews with six designers (a cognitive psychologist, a practicing physicist, and four science educators) were analyzed to identify their contributions during the phases of analysis, development, and evaluation to create educative features for developing pedagogical content knowledge (PCK). Findings articulate specific educative features that can contribute to supporting PCK and thereby supporting instructional performance. Findings also reveal the proactive and reactive nature of designer contributions, describing different ways in which designers provide specialized inputs from a disciplinary perspective. Further, this study shows how designer contributions intermeshed, with contributions from one discipline shaping the work of colleagues, and thereby coordinating varied inputs to yield coherent educative materials. In addition, theoretical insights and recommendations for research on the nature of collaborative interdisciplinary design processes and implications for practice are given for supporting designers working in interdisciplinary teams to create educative curriculum materials for teacher (and student) learning.

This chapter is based on:

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2021). Designing educative curriculum materials in interdisciplinary teams: Designer processes and contributions. *Instructional Science, 49*(2), 249-286.

Teachers' knowledge of a subject for teaching and the nature of supportive materials for enactment influence the quality of classroom instruction (Hill & Charalambos, 2012). Materials designed to support both teachers' and students' learning simultaneously are referred to as educative (Davis, Palincsar, Arias, Bismack, Marulis & Iwashyna, 2014). This study focuses on educative features for developing teachers' pedagogical content knowledge (PCK). PCK is knowledge relevant to teaching specific topics (Grossman, 1990), and comprises components such as knowledge of instructional strategies and student thinking (see Theoretical Framework for more details on PCK components). Teachers rely on their PCK to (re)design, customize or curate the learning opportunities in their classrooms (McKenney, 2017). Indeed, recent research shows that teachers' PCK affects their instructional skills in the act of teaching, such as explaining scientific phenomena to students (Kulgemeyer et al., 2020).

The importance of educative materials has been widely recognized in science education research (Krajcik & Delen, 2017). This is largely because they have been shown to positively influence both teaching and learning in science (Pareja Roblin, Schunn, & McKenney, 2018; Bismack, Arias, Davis & Palincsar, 2015). For example, educative materials highlighting specific teaching moves and language about scientific practices help teachers engage students in key scientific practices, such as making observations and predictions (Arias, Bismack, Davis & Palincsar, 2016). Similarly, supports foregrounding specific strategies and representations help teachers facilitate students' understanding of science content (Schneider & Krajcik, 2002). Furthermore, instructional supports that help teachers understand student thinking enable them to customize classroom environments to provide timely, targeted guidance to foster student learning (Matuk, Linn & Eylon, 2015).

Studies on educative materials have focused on heuristics and principles for designing such materials (Davis & Krajcik, 2005; Davis, Palincsar, Sean-Smith, Arias, & Kademian, 2017); specific educative features (e.g., Rosemann, Herrmann-Abell, & Koppal, 2017; Schneider & Krajcik, 2002); teachers' use of educative materials during classroom enactment (e.g., Arias et al., 2016); and the impact of the materials on PCK (e.g., Marco-Bujosa, McNeill, González-Howard & Loper,, 2017; Schneider 2013). Furthermore, the frequency and quality of supports in existing educative materials have been evaluated, yielding specific recommendations for facilitating teacher learning (Beyer, Delgado, Davis, & Krajcik, 2009). However, what is less understood are the systematic processes for creating educative materials that can inform instructional design in different contexts (Davis et al., 2014).

3.1 Problem statement

The literature on curriculum and instructional design points to general processes and models (e.g., Gustafson & Branch 2002; Thijs & van den Akker, 2009), and offers generic guidance through case examples for teaching instructional design (Ertmer & Quinn, 2007). A few studies also document design processes for developing educative science materials, describing measures taken to yield specific educative features (Davis et al., 2014; Kruse, Howes, Carlson, Roth, & Bourdélat-Park, 2013; Roseman et al., 2017). Furthermore, collaborative design processes have been investigated in the contexts of curriculum (Barber, 2015), technology-enabled immersive learning systems (Flood, Neff, & Abrahamson, 2015), and informal science learning spaces (Wang, 2014). Whereas this line of work offers valuable insights into how designers from different backgrounds make specific contributions and tackle shared problems through dialogue and co-constructed artifacts, it does not elucidate their processes for producing *educative materials*. Specifically, what is missing is fine-grained information about processes and inputs of designers with different disciplinary backgrounds, clarifying how they contribute based on relevant expertise and synthesize their perspectives to create educative science materials.

This is an important gap to address because designing educative science materials requires simultaneous attention to subject matter, student understandings, and instructional approaches. To do so, design teams may require the expertise of scientists, educational psychologists, and those with teaching experience at target grade levels. But how can a disparate team of designers coordinate their inputs to create educative science materials that support the development of multiple PCK components, such as teacher knowledge of student thinking, instructional strategies, and assessments? PCK components are interconnected (Magnusson, Krajcik, & Borko, 1999; Park & Chen, 2012; see Theoretical Framework for details); hence, educative materials must support them together. Research is needed to ascertain, for example: How do designers with different expertise contribute to supporting specific PCK components? Do all designers attend to the same concerns about PCK across phases of the design process? How do designers negotiate differing perspectives, and how are designer tasks integrated to yield coherent educative features that can support the development of PCK?

Detailed knowledge about interdisciplinary collaboration is important because designers tend to approach shared problems and goals with varied knowledge bases (Fischer & Ostwald, 2005). They may also initially value different and possibly conflicting strategies for teaching and learning (Barber, 2015). Further, designers often have limited understanding of how other designers' work is pertinent to their own (Arias, Eden, Fischer, Gorman, & Scharff, 2000). Whereas each designer domain may offer unique and valuable input, innovative solutions stem from integration, which is notoriously difficult. Therefore, detailed insights into collaborative interdisciplinary processes for designing educative curricula can shed light on how to optimize and coordinate varied designer expertise to help teachers support custom learning opportunities for their students.

3.1.1 *Goal of the study*

The goal of this study was to yield a detailed understanding of collaborative interdisciplinary processes of designers geared towards supporting teachers' PCK. Specifically, the study aimed to generate insights on how designers make discipline-based contributions and coordinate their contributions to systematically create coherent educative materials. Further, based on these theoretical insights, the study also sought to provide practical recommendations for designers engaging in interdisciplinary curriculum design. In so doing, the study aimed to contribute to the knowledge base on designer expertise and processes, especially in the context of educative science materials. To that end, the retrospective analysis focused on producing a worked example of the interdisciplinary design process behind a robust primary school science curriculum* containing many educative supports for teachers. Comparable to process-oriented worked examples (see Van Gog, Paas, & Merriënboer, 2004), this example delineates key activities and specialized inputs of designers with different disciplinary backgrounds to produce educative features of a high-quality science curriculum. The study was guided by the following research question: *Throughout the design process (analysis, development and evaluation), how do designers create educative materials that support development of PCK, and in so doing, what is the contribution of designers with different disciplinary backgrounds?*

*NB: In this study, we use Taba's (1962) classic definition of curriculum as meaning "a plan for learning." This includes broader processes and goals that span larger chunks of time (e.g. unit objectives addressed over weeks or months), specific plans for learning and instruction that are enacted within smaller chunks of time (e.g. activities lasting several minutes to an hour), and information about bringing them into alignment (e.g. instructional sequences or lesson structures).

3.2 Theoretical framework

3.2.1 Three Generic Phases of Design

Across disciplinary conventions, three phases of (science) curriculum design can be distinguished. The design process generally commences with an *analysis* phase in which designers work towards defining the problem and range for improvement (Thijs & van den Akker, 2009). They analyze the contexts where the curriculum will be used and the needs of the target teacher and student audience (Edelson, 2002; McKenney & Reeves, 2012). Typical activities include reviewing literature to understand how other designers have formulated and tackled similar problems (McKenney & Reeves, 2012). The review may include: learning theories and prior research on curriculum materials to support teachers' knowledge (Kruse et al., 2013; Roseman et al., 2017); science standards frameworks to identify what scientific concepts and practices need to be taught (Krajcik et al., 2008; Songer 2006); and policy documents providing evaluation criteria for curriculum materials (Roseman et al., 2017). Designers may also analyze the content of existing science materials to identify instructional requirements and opportunities related to science concepts, practices, and assessment of student learning (Davis et al. 2014). Additionally, designers collect data to conduct a needs and context analysis (Edelson 2002). Examples of data sources include: surveys given to school personnel (McKenney & Reeves, 2012); lesson observation protocols; teachers' instructional logs and interviews; and students' pre-post test data to understand teachers' instructional decisions and challenges in using existing curriculum materials (Davis et al., 2014). The analytic activities help designers define the problem, derive overall goals, and generate initial design principles and requirements. The preliminary design specifications guide designer work: the intended outcomes (the target learning objectives); their envisioned enactment (what instructional activities to help achieve those outcomes look like); and the written curriculum (including supports for teachers and students) (Roseman et al., 2017; McKenney & Reeves, 2012).

Following analysis, a *development* phase involves exploring ideas for potential solutions, mapping details and constructing prototype solutions (McKenney & Reeves, 2012). In this phase, designers take concrete steps to respond to the goals and contextual needs identified previously (Edelson, 2002). For example, based on content analyses and data from teachers' enactment of existing materials from the preceding phase, designers may prepare supports such as content storylines and concept maps (Davis et al., 2014). Notable development activities include review of policy documents and prior research to specify science learning goals and sequences of instructional activities (Krajcik et al., 2008; Songer, 2006). In so doing, designers may choose a limited set of scientific ideas to create coherent content storylines and other supports to depict the storylines (Roseman et al., 2017). The literature review may also focus on students' difficulties, recommended approaches in the field, and strategies for engaging students in scientific practices to create appropriate educative supports (Davis et al., 2014). Additionally, designers may utilize frameworks-based rubrics specifying criteria for designing educative supports to help teachers understand students' conceptions and to assess students' learning (Roseman et al., 2017). Other activities include seeking insights from scientists serving as subject matter experts to identify which scientific facts to address (Songer, 2006). Based on the activities in this phase, designers plan measurable intended outcomes (Gustafson & Branch, 2002), identify target content (Smith & Ragan, 1999), prepare instructional tasks and sequences aligned with those outcomes (Krajcik et al., 2008; Songer, 2006), and generate written materials according to design specifications (McKenney & Reeves, 2012).

Finally, designers conduct both formative and summative *evaluations* – collecting data to guide revisions and to determine the impact of the curriculum (Gustafson & Branch, 2002). Key activities include: using criteria in frameworks-based rubrics to assess quality and coherence of educative supports (Kruse et al., 2013; Roseman et al., 2017); gathering external expert appraisal on matters such as accuracy of scientific ideas presented in the materials (Davis et al., 2014; Thijs & van den Akker, 2009); and conducting pilots of preliminary prototypes and field tests of more mature versions of the curriculum in classrooms (McKenney & Reeves, 2012). Designers collect data from varied sources such as observations of classroom enactments, teachers' interviews and instructional logs, written tests of teachers' knowledge of science subject matter, curriculum and students' thinking, and students' work and written tests of students' learning outcomes (Davis et al., 2014; Kruse et al., 2013; Roseman et al., 2017). Based on evaluation data, designers make required revisions to the key curriculum features (redesign).

3.2.2 Pedagogical content knowledge and educative curriculum materials

When designers perform the above-mentioned systematic, iterative processes to create materials that support teacher learning, they typically generate features that support the development of teacher PCK, which is broadly conceptualized as "teachers' understanding of how to help students understand specific subject matter" (Magnusson et al., 1999). This knowledge is specific to subjects (e.g., science) and topics within those, and teachers draw on this knowledge both in the act of teaching and in reasoning about and planning for teaching (Kirschner, Fischer, Borowski, Gess-Newsome, & von Aufschnaiter, 2016). The present study examines interdisciplinary designer work in supporting *personal PCK*, which is knowledge held by individual teachers, and *enacted PCK*, which is knowledge utilized in the act of teaching (Kulgemeyer et al., 2020). The study focuses on the following five components of PCK: knowledge of student thinking, instructional strategies, curriculum, assessment, and subject matter. This section defines each component, describes its importance, and provides examples of relevant educative materials. The framework on PCK components served as an analytical lens to interpret designer inputs and activities in the context of educative curriculum materials.

3.2.2.1 Knowledge of student thinking

Knowledge of student thinking is considered to be a central component of teachers' PCK (Van Driel, Verloop, & de Vos, 1998). This component includes knowledge of students' typical understandings, preconceptions and misconceptions of specific science topics, the reasons behind their thinking, and knowledge of what makes specific topics easy or difficult for students to learn (Cochran, King, & DeRuiter, 1991; Kirschner et al., 2016; Magnusson et al., 1999; Shulman, 1986; Tamir, 1988; Veal & MaKinster 1999). This study defines knowledge of student thinking in science as the *knowledge of students' typical conceptions (including preconceptions and misconceptions), the reasoning behind their thinking, and their learning needs and difficulties in relation to specific science topics.*

Knowledge of student thinking is important to understand their students (Magnusson et al. 1999) and to select appropriate instructional strategies to support students' learning of specific topics (Gess-Newsome, Taylor, Carlson, Gardner, Wilson, & Stuhlsatz, 2017; Park & Chen, 2012). To this end, educative features include overviews of typical student misconceptions and their instantiations in student work (Roseman et al., 2017). Additionally, lesson-embedded notes point to students' preliminary understandings and possible reasons behind their difficulties (Schneider, 2013; Schneider & Krajcik, 2002).

3.2.2.2 Knowledge of instructional strategies

Knowledge of instructional strategies is also considered to be a central component of teachers' PCK (Van Driel et al., 1998). This component consists of teachers' knowledge of strategies to represent topics in a subject and to make them comprehensible to students (Shulman, 1986). It includes knowing about representations (i.e., models, analogies, explanations and examples) and activities (i.e., investigations, experiments and simulations) (Magnusson et al., 1999; Park & Oliver, 2008; Veal & MaKinster, 1999) in relation to specific topics. Some conceptualizations of this component also include strategies that are applicable to science as a subject compared to other subjects, for example, instructional sequences like the learning cycle (e.g., Park & Oliver, 2008; Veal & MaKinster, 1999), and phases of particular kinds of science lessons (Tamir, 1988). This study defines knowledge of instructional strategies as the *knowledge of subject-specific (general) instructional strategies in science like phases of inquiry-based lessons as well as knowledge of topic-specific strategies like investigations, questions, and explanations to help students understand scientific concepts and practices.*

To help teachers understand and enact appropriate instructional strategies, scientific practices like argumentation are defined (Marco-Bujosa, McNeill, Gonzalez-Howard, & Loper, 2017) and specific strategies like modeling are provided to help them engage students in the practices (McNeill, 2009). Educative features also include rationales of representations and activities (Roseman et al., 2017); boxed notes indicating key concepts to highlight to students (Arias et al., 2016); and short scenarios and questions to model teacher language (Schneider, 2013; Schneider & Krajcik, 2002).

3.2.2.3 Knowledge of curriculum

Knowledge of curriculum refers to teachers' knowledge of the learning goals, activities and materials of different curricular programs available to teach particular subject matter and topics, and knowledge of horizontal and vertical curricula in the subject area (Grossman, 1990; Magnusson et al., 1999; Shulman, 1986; Park & Oliver, 2008). Additionally, this component can include knowledge of mandated goals at particular grade levels (Magnusson et al., 1999); how topics are organized (Marks, 1990); pre-requisite concepts to learn particular topics (Tamir, 1988); and core concepts of the topic and central and peripheral ideas and activities in relation to the overall curriculum (Park & Chen, 2012). The present study operationalizes this component as the *knowledge of topic organization and core concepts to teach, of overall learning goals and activities, and of concepts addressed vertically during prior and successive units of the curriculum.*

Knowledge of curriculum guides teachers in adapting activities and eliminating peripheral activities or ideas in science instruction (Park & Chen, 2012). To develop this component, unit overviews clarify topic organization, describing relationships between scientific concepts and their development through lessons (Schneider & Krajcik, 2002). Overviews prior to sections of lessons also explain how the lessons contribute to the unit (Roseman et al., 2017). Finally, lesson-embedded content storylines describe how a lesson relates to the overall unit, the intended scientific concepts and their relevance to subsequent lessons (Arias et al., 2016).

3.2.2.4 Knowledge of assessment

Fourth, *knowledge of assessment* consists of knowledge of the aspects of science learning that are critical to assess in a unit of study (Park & Oliver, 2008). It extends beyond conceptual understanding to include dimensions of scientific literacy (Magnusson et al., 1999) and particular skills (Tamir, 1988). This component further includes knowledge of different methods of assessment, including particular activities, procedures or approaches applicable to a given unit of study (Magnusson et al., 1999; Park & Oliver, 2008); particular instruments (Tamir, 1988); and knowledge of the strengths and limitations of the different methods (Magnusson et al., 1999). Topic-specific pre-tests, different lines of questioning, and student-generated products such as journal records, drawings and models are examples of assessment methods. The present study operationalizes knowledge of assessment as the *topic-specific knowledge of key conceptual understandings and scientific disciplinary practices to assess, and of various methods (activities or instruments including student-generated products) for assessment relevant to the unit of study.*

The assessment methods may be used formatively to gather and interpret evidence of students' understanding related to the learning goals and to identify next steps in teaching and learning (Harlen, 2006). Indeed, formative assessment is critical in supporting scientific inquiry and practices (National Academies of Sciences, Engineering and Medicine, 2017), and is emphasized in recent research on fostering science teachers' professional learning (Furtak et al., 2016). This component has implications for the two central components of knowledge of student thinking and of instructional strategies. Knowing different formative assessment methods may help teachers identify their students' thinking and modify instruction to better facilitate students' learning (Park & Chen, 2012). Educative materials for assessment include pointers at the beginning and end of lessons on assessing specific conceptual understandings and skills in student-generated artifacts (Schneider & Krajcik, 2002), and rubrics and sample student work with recommended teacher feedback on students' understandings (Davis et al., 2014).

Finally, while there is little dispute that *subject matter knowledge* is a crucial component of a teacher's professional knowledge base (Kind 2009; Tobin, Tippins, & Gallard, 1994; Veal & MaKinster, 1999), expert opinions differ as to whether or not it should be included as a PCK component (Kind, 2009; van Driel et al., 1998). The present study does not tackle this divergence, but it does include attention to subject matter knowledge because educative curricula must support teachers' understanding of (scientific) concepts and practices (e.g., Davis & Krajcik, 2005).

3.2.2.5 Subject matter knowledge

Subject matter knowledge includes understanding not only of the major facts and concepts of a subject, or their interrelationships, but also of the processes by which those ideas are established (Grossman, 1990; Shulman, 1986; Tamir, 1988). It may be topic-specific (Veal & MaKinster, 1999) and includes understanding the importance of a topic to the discipline (Shulman, 1986). This study operationalizes knowledge of subject matter as the *topic-specific knowledge of the meaning of key scientific facts and principles and theoretical frameworks, and includes knowledge of the importance of the topic and knowledge of disciplinary practices by which the content is established.*

Educative supports for subject matter knowledge include overviews with definitions and rationales of scientific practices (Bismack et al., 2015; Davis et al., 2014), and explanations of scientific concepts at a level beyond the intended student understanding (Schneider & Krajcik, 2002). Explanations may also appear in content charts and boxed notes in background material or they may be embedded in the directions for specific lessons (Arias et al., 2016; Schneider, 2013).

3.2.3 Designing in interdisciplinary teams

Curriculum design often involves collaboration among designers of different disciplinary backgrounds. Interdisciplinary collaboration is an interpersonal process for efficient attainment of goals that cannot be attained when individual professionals act independently (Bronstein, 2003; Bruner, 1991). It is important because all of the relevant and requisite knowledge to yield solutions for long-term, complex design endeavors is not contained within a single designer's contributions but is distributed among designers (Arias et al. 2000). Through dialogue and establishment of shared vision and goals, the resultant design reflects synergies among designer work, taking advantage of varied expertise to craft solutions that are greater than any individual designer contributions (Barber, 2015).

Models of interdisciplinary collaboration highlight specific components of desirable interactions (Bronstein, 2003). For example, a core component is interdependence among professionals to achieve their tasks, in which they communicate formally or informally via oral or written means and show respect for colleagues' contributions. And another core component is collective ownership of goals, in which professionals take shared responsibility throughout the process for collectively formulating and reaching those goals.

The literature also shows how designers make unique contributions based on their expertise and how they interact with one another to generate new insights. For example, in designing engineering challenges for tinkering in informal learning spaces, science educators contribute methods of accessible learning, while practicing engineers offer inputs to make content relevant and authentic (Wang, 2014). And in designing virtual tutors, computer scientists and learning scientists engage in analysis, communication, and reflection to understand shared design issues with embodied interactions (Flood et al., 2015). In so doing, studies have shown the importance of designer interactions around *boundary objects* - shared artifacts to establish common ground (Barber, 2015; Fischer & Ostwald, 2005). This is because collaboratively created artifacts, such as documents of plans or prototypes, externalize designer thinking and provide a basis to communicate and develop new understandings (Fischer & Ostwald, 2005; Flood et al., 2015). The use of boundary objects is especially important in interdisciplinary design teams because these function as *communities of interest,* where members from different fields of practice come together to tackle problems of shared interest (Fischer & Ostwald, 2005). Whereas multiple backgrounds offer potential for creative solutions, doing so requires designers to establish shared understanding of design tasks, for which boundary objects play a crucial role.

3.3 Methods

3.3.1 Case study

To gain insight into how designers with different disciplinary backgrounds contribute to creating educative materials that support development of PCK, a qualitative interpretive case study (Merriam, 1988) was undertaken. This method was deemed suitable because the intended outputs were a detailed worked example of a finished curriculum product and its design process (Howard et al., 2012). The curriculum was designed at an independent STEM educational research and development organization in the USA. First, curriculum projects were sought using the following criteria: (i) target audience of K-12 teachers and learners; (ii) stand-alone school curriculum (as contrasted with supplementary or out-of-school curriculum); (iii) intention to support students' understanding in science; and (iv) evidence of positive learning outcomes. This yielded six potential cases. The present case was selected for this analysis because it focused on educative supports. The researchers did not contribute to developing the written curriculum materials, but for this study they were granted access to documentation about the development of the curriculum and opportunities for in-depth conversations with the designers. This access was critical to gather detailed data for the qualitative case study.

This case constituted a stand-alone, inquiry-based longitudinal curriculum for grades 3-5. As stated in the project's grant proposal, the curriculum was inspired by research on learning progressions on the nature of matter that "is organized around big ideas in science and inquiry practices," "inquiry-based learning and (formative) assessment" (Harlen, 2006), and an established model of teacher professional learning (Harlen & Altobello, 2003). A nine-week unit was developed for each of the three grades, involving a coherent sequence of investigations with hands-on explorations and discussions to help students gather data and to make meaning of the data and scientific principles. The units for Grades 3 and 4 had 17 investigations each and the Grade 5 unit had 18 investigations. The curriculum materials consisted of a teacher guide, student notebooks, and a hands-on kit.

This curriculum was chosen for its high quality and potential insights into educative supports and the collaborative interdisciplinary nature of its design process. Field tests of the curriculum revealed positive shifts in teacher understanding of the major concepts or topics in the curriculum after teaching it. For example, an external evaluation report for the Grade 3 unit stated that "all teachers reported a better understanding [of the content] in at least one [section of the curriculum] (materials, weight, standard measure, volume). Where change occurred, all changes were positive, teachers came to a clearer understanding of the topic." Furthermore, observations of their teaching practice during curriculum enactment indicated a greater familiarity with, and ability to implement, inquiry-based instruction. For example, an external evaluation report for the Grade 4 unit stated that all five field test teachers were scored higher on the RTOP[3] for the [curriculum] lesson than the baseline lesson enacted before the curriculum field test. The ratings increased to 57, 56, 64, 55 and 56 from 40, 25, 35, 42, and 49 respectively for the five field test teachers. There was an increase in teachers' attempts to engage students in making predictions/estimations and/or hypotheses and devising means to test them, and in thought-provoking activity that frequently involved the critical assessment of procedures. Furthermore, teachers' questioning strategies changed from the baseline lesson prior to the field test to the curriculum lesson. For example, an external evaluation report for the Grade 3 unit mentioned that teacher questions changed from eliciting recall and comprehension to probing and guiding students' conceptual understanding. The percentage of questions higher than recall questions (e.g., asking students to provide evidence for their answers; helping students build on/refine one another's responses and understanding) on a sub-section of the INCRE observation protocol increased to 86%, 29% and 55% from 0%, 0%, and 35% respectively for the three field test teachers.

Additionally, as stated in an annual report to the funding agency, field tests tracking progress of treatment and control group students over three years showed

---

[3] RTOP stands for Reformed Teaching Observation Protocol, a standardized instrument to determine the degree of reform in K-20 classroom instruction in science and mathematics. It has a maximum possible score of 100.

that the curriculum helped students make progress in understanding ideas related to a network of concepts, including weight, volume, and material things. For instance, statistically significant differences were found on assessment tasks about properties of tiny things, with the treatment group outperforming the control group at all three grade levels. The treatment group also made statistically significant progress compared to the control group in understanding that tiny invisible things have weight. And on a water displacement task assessing students' understanding of volume, too, the treatment group statistically outperformed the control group. Finally, personal communication with the curriculum project's principal investigator revealed that the curriculum continues to be in use.

3.3.2 *Data sources*

Consistent with recommendations for case study research (Guba, 1981; Yin, 2014), this study gathered evidence from multiple data sources, namely project documents, finished curriculum materials, and transcripts of interviews with the designers. Table 3.1 maps the data sources and their corresponding information.

Table 3.1: Data sources and their corresponding information.

Data Sources	**Designers' Disciplinary Contributions**	**Design Process Phases**	**PCK Components**	**Educative Features**
Project documents (grant proposal, prototypes of educative materials, memos, classroom testing notes, progress reports to funding agency, external evaluation reports)	X	X	X	X
Finished educative materials	Not Applicable	Not Applicable	X	X
Interview transcripts	X	X	X	X

3.3.3 *Participants*

Following purposeful and referral sampling techniques, the researchers recruited six participants based on their disciplinary backgrounds and stages of work in the curriculum design. The principal investigator of the curriculum project served as informant for further sampling (Yin, 2014), presenting a preliminary list of candidate participants who, in turn, provided subsequent referrals. The list below summarizes information about the six participants, stating the alphanumeric codes (used in the results section), their disciplinary backgrounds, and relevant experience.

- P1: Science Educator (primary school teaching, design of science curriculum and teacher PD)
- P2: Science Educator (engineering, design of science curriculum and teacher PD)

- P3: Science Educator (primary school teaching, design of science curriculum and teacher PD)
- P4: Science Educator (engineering, primary school teaching, design of science curriculum and teacher PD)
- P5: Cognitive Psychologist (research on conceptual change and learning progressions in science)
- P6: Practicing Physicist (Subject matter knowledge of science)

Owing to commonalities in the backgrounds of P1, P2, P3, and P4, namely their experiences with designing science curriculum and teacher PD, and primary school teaching in the case of three of the designers, these four designers were treated as a single group – "science educators" – for data analysis and presentation of findings. This treatment of the four science educators as a single unit in the data analysis was justified by their overlapping expertise, and by the goal of being able to highlight how the science educators' contributions differed from those of the physicist and the cognitive psychologist, and reveal patterns in disciplinary contributions.

3.3.4 Procedures

Researchers prepared an initial project summary and timeline depicting the curriculum, its design activities and outputs. Next, they conducted prolonged interviews with each participant (Yin, 2014); each interview lasted approximately two hours. The project summary and timeline was used to facilitate participants' recall during the interviews. A semi-structured protocol guided the interviews, containing open-ended questions about curriculum materials such as, "How did your curriculum support teachers' and students' understanding of science concepts?", and "How did your curriculum support teachers and students to engage in scientific inquiry?" There were also questions about design process phases. For example, a question for the analysis phase was, "What was your role in the project's activities to learn about the target audience, their needs and abilities, and any barriers to teaching and learning science?" Similarly, sample questions for the development and evaluation phases were, "What was your approach for designing the [specific educative material]?", and "What was your role in testing the curriculum?" All interviews were audiotaped and transcribed.

3.3.5 Data analysis

The data were coded twice, deductively and inductively. The deductive approach was undertaken in four phases, namely to examine: (i) designer work at the curriculum level; (ii) PCK components in designer work; (iii) educative features in relation to the PCK components; and (iv) design process phases related to the PCK components and educative features. Across all deductively coded data, inductive analysis was then undertaken. Each of these processes is elaborated below.

3.3.5.1 Deductive analysis: Designer work at the curriculum level

In the first phase, the interview transcripts were examined to identify key aspects of designer work at the curriculum level (intended outcomes, envisioned enactment, written curriculum, and design processes; see Table 3.2). The first author and another researcher independently coded one transcript at a time at the sentence-level. They resolved discrepancies through discussion and established final coding decisions through consensus. This process continued until an acceptable level of inter-rater reliability was attained (Cohen's Kappa was 0.79[4]). The first author then coded the remaining dataset.

3.3.5.2 Deductive analysis: PCK components in designer work

In the second phase, the interview and document data were coded for designer work on the different PCK components as defined in the conceptual framework. Specifically, the data were analyzed for how designers supported teacher knowledge of student thinking, instructional strategies, curriculum, assessment, and subject matter. Table 3.2 gives an overview of the codes.

Table 3.2: Deductive coding scheme (first and second phases).

Code	**Description**	**Sample quote**
	Designer Work at Curriculum Level	
Intended Outcomes	The learning objectives for the curriculum that the designers set out to attain	The goal was to develop [students'] understanding of properties of matter, at least leading up to being ready to learn about the particulate nature of matter.
Envisioned Enactment	The designers' vision for teacher enactment and student experiences	So the model was that you start with helping the learner to become familiar with his or her ideas, to have first-hand experiences that would provide additional data, and that through discussion, new meaning would develop.
Written Curriculum	Written supports for teachers and students	The purpose of [child and scientist essays] was to help the teacher understand how a child thinks about these concepts, what the core concepts are, and to help them think about what is the real science behind this?
Design Processes	Designer considerations and measures to generate and refine the curriculum features	So there was some kind of planning where we were writing sequences of concepts in little boxes, about what would happen in [grades three, four, five]. There was an initial grid, and then after piloting it, P4 would fix it and rearrange it.
	PCK Components in Designer Work	
Student Thinking	Supporting teacher knowledge of students' typical conceptions and possible difficulties	Child essays were created to help teachers] think a little bit differently - that here are some rich understandings your [students] have, but are really different from the scientist's, so [teachers] begin to think about,

---

[4] The study reported in this paper was part of a larger research project on science curriculum design. The Cohen's Kappa was calculated for a set of 13 codes associated with the larger research project.

		how can you acknowledge where your students are starting.
Instructional Strategies	Supporting teacher knowledge of general and specific strategies to teach concepts and practices	We realized that when we were working in classrooms, that oftentimes, there weren't class discussions, Meaning Making discussions, and so the meaning making discussions were in the curriculum. And so one of the things that came again from that was that every discussion would begin with a question, and that the discussion would have the same components to it, in the same way that the lesson had the same components.
Curriculum	Supporting teacher knowledge of the organization of the content, and overall learning goals and activities	They were like grids, where you had to write down. And there'd be two of them, for the third grade, for instance. And one of them would be how the concepts were developing, day by day by day, and how you're sort of building. And the other one would be like the activity that you did day by day by day.
Assessment	Supporting teacher knowledge of the scientific concepts and practices to assess, and of activities and student work to use as assessment methods	We didn't want [the formative assessments] to be too long or too complicated, so how do you do this in a very concise way? And then I had to go looking for resources, and the idea was that your source of information was either what kids write, or what they say, or what you watch them do
Subject Matter	Supporting teacher knowledge of the target concepts and practices and their importance.	I guess my first task was to try to answer the question for myself. So if P1 would call up and say, we need an essay on why the idea of matter is important. So the first thing I would have to do is, I would have to really think about it, and sort of come up with an answer that satisfied me about, why is it scientifically an important concept. And then I would have to try to think of a way to express that to the intended audience.

3.3.5.3 Deductive analysis: Educative features in relation to the PCK components

Furthermore, the educative features of the written curriculum were mapped to the PCK components. A total of 10 relevant educative features were identified in the teacher guide. They were deemed relevant if they were aligned with one or more of the PCK components as defined in the conceptual framework of this study. There was a total of 52 lessons and 14 sections across the three grade-level units of the curriculum. One feature was designed to be referred to across the whole curriculum; one feature was designed for use at the unit level; two features at the section level; and five features at the lesson levels. Finally, one feature was designed for use at multiple levels. The subsequent paragraphs describe each feature in more detail.

At the curriculum level, the Curriculum Concepts Chart (C-C) portrayed the three-year progression of student understandings of a network of fundamental concepts, consistent with the learning progression approach undergirding the curriculum. At the unit level, the Curriculum Overviews (C-O) summarized learning activities of the unit. At the section level, the Child Essays (ST-CE) and Scientist Essays (SM-SE) clarified typical student understandings and important scientific concepts and practices respectively to help teachers prepare prior to enactment. At the lesson level, the Consistent Tripartite Structure (IS-CTS) provided a broad lesson structure in-the-moment to help teachers facilitate student engagement in scientific inquiry practices. The Boxed Notes at the lesson level reminded teachers in-the-moment about possible student conceptions (ST-BN), instructional strategies to respond to student ideas (IS-BN), and provided conceptual clarifications respectively (SM-BN). The Formative Assessments (A-OW) at the lesson level pointed teachers to various activities and instruments (including student-generated products) to assess students' understanding of scientific concepts and practices. Finally, the Curriculum Narratives (C-N) highlighted topic organization and learning goals and activities at the unit, section, and lesson levels.

3.3.5.4 Deductive analysis: Design process phases for PCK components and educative features

The design processes behind the PCK components an**d** educative features were also examined at a fine-grained level in terms of the analysis, development, and evaluation phases (see Table 3.3). Further, inputs and activities of designers were analyzed in light of their discipline-based contributions towards particular PCK components and educative features. During this process, the project documents helped "corroborate and augment" (Yin, 2014, p.107) the interview data, confirming and elaborating those with examples and culling information not yielded by the interviews.

Table 3.3: Codes for design process phases related to PCK components and educative features.

Code	Description	Example
Analysis	Designer work to generate overall goals, initial design requirements, and specifications	The [cognitive psychologists] fleshed [the original learning progressions framework] out, and they made this much more explicit roadmap about how they actually thought things were going to grow. And so that happened at the beginning of the project.
Development	Designer work to plan target content, instructional activities and sequences, and create written materials	I would put together a sequence that I thought would work towards developing a better understanding of material properties, for example. Just an outline. And then I would sit down with P3 and P2, and they would think about it, and troubleshoot it.
Evaluation	Designer work to test and refine	I remember seeing so vividly [in pilot classrooms] was that you'd tell them to make observational

	prototypes and more advanced versions of the curriculum	drawings, and we thought that they were going to very carefully sketch. But they weren't doing any careful observation. Their drawings didn't reflect the data at all. So you come back and you say, there's got to be something about observational drawings [in the written curriculum].

3.3.6 Inductive analysis

Undertaken across the entire coded data set, the inductive analysis yielded two main themes. The first theme pertained to the nature of designer contributions, which can be viewed as proactive and reactive. The proactive contributions involved: (i) producing outputs for specific PCK components (e.g., essays by the physicist explaining scientists' understanding of target concepts) and/or (ii) undertaking specific design measures (e.g., reviewing existing formative assessment frameworks). By contrast, the reactive contributions involved providing feedback on colleagues' outputs (e.g., the science educators providing feedback on drafts of unit outlines based on consideration of children's capacities). The second theme can be characterized as intermeshing, which revealed how an output created by designers from a specific disciplinary background was shaped by proactive and/or reactive input(s) of designers of another disciplinary background (e.g., the science educators drafted key scientific ideas for teacher knowledge to be highlighted in essays developed by the physicist and cognitive psychologist respectively). This term was chosen (over similar others, such as interlinked or connected) to highlight a certain characteristic of the operations of the design team – specifically, that designer inputs from different areas of expertise enabled and specified the work such that the varied disciplinary contributions blended together to result in a coherent output. The authors discussed all mapping in the data until 100% consensus was reached.

3.4 Results

As stated before, the data analysis revealed that designers created 10 educative features to support the PCK components. This section presents findings about how designers with different disciplinary backgrounds contribute to creating educative features throughout phases of the design process (analysis, development, and evaluation). Table 3.4 depicts the educative features, including their descriptions, samples, and the frequency with which they appeared in the teacher guide.

Table 3.4: Educative features supporting (development of) PCK components.

Educative Feature and frequency[5]	**Description**	**Samples**
Student Thinking-Child Essays (ST-CE) (n =13)	Explain children's understandings and difficulties with target concepts and scientific practices; presented separately from lesson plans for each section of a grade unit	Excerpt from Grade 5 essay describing children's challenges in understanding evaporation and condensation of water: [Children] must use the existence of invisible entities—gases—which they do not clearly understand and may not even believe exist—to explain visible events. Some may say that the water has "gone into the air" or even use the word "evaporated." They no longer think it retains its identity as water. Excerpt from a Grade 4 essay on the challenges of developing explanations based on data and evidence: Young children are constantly moving from evidence (specific observations) to claims (generalizations based on these observations) in their everyday lives. But children are not conscious of what they are doing in this process. One challenge, then, is to get them to reflect on and conceptualize the process itself, explicitly distinguishing "the claims" from "the evidence." This can be hard for children because for them claims and evidence blend seamlessly together into simply "the way things are." When asked to explain an observation (Why do you think this cylinder is heavier?), they might just repeat the observation (because it feels heavier) rather than proposing a deeper explanation. Another challenge for teachers is that, left unguided, children may notice or pay attention to things in a situation that the teacher thinks are irrelevant and fail to notice things that the teacher thinks are highly relevant. For example, when exploring a data table in search of patterns in the numbers, students might be looking for patterns based on addition or subtraction rather than multiplication or division; hence they may fail to find any meaningful generalization (such as when I double the volume of the water, I double its weight too).

---

[5] Frequency means number of instances across all three grade-level units of the curriculum.

Student Thinking-Boxed Notes (ST-BN) (n = 30)	Highlight student difficulties or alternative ideas to expect in-the-moment of teaching; embedded in lesson plans	Note from Grade 4 investigation on measuring volumes of irregularly shaped objects: Fourth graders will sometimes confuse volume with surface area, counting the two-dimensional "faces" of the cubes on the outside of the block instead of the three-dimensional cubes that make up its volume.
Instructional Strategies-Boxed Notes (IS-BN) (n = 32)	Provide topic-specific strategies to address students' initial ideas or difficulties and subject-specific strategies to enact scientific practices; embedded in lesson plans	Note from Grade 5 investigation on comparing the properties of ice and water: A common misconception is that the condensation is water that leaks through the plastic. If someone suggests this, show the class the bottle holding room temperature water and point out that no water is leaking through that plastic.
Instructional Strategies-Consistent Tripartite Structure (IS-CTS) (n = 47)	Structure embedded in lesson plans to integrate concepts with scientific practices: Ask the Question (AQ), Investigate & Share (IS), and Make Meaning Discussions (MM); color-coded text distinguishes procedural steps and tips from recommended teacher language for specific questions, explanations or examples to guide students' thinking	In a Grade 4 investigation on water displacement, teacher poses the question in AQ: What causes the water level to rise? Supporting questions include, What do you predict will happen when I add this larger rock to this container of water? What will happen when I put this smaller rock into the second container? Why do you think one rock displaced more water than the other? In IS, students record their predictions, data, conclusions and share data with the class. In MM, teacher restates the question and prompts students to discuss data and construct explanations. The supporting questions include, Can you claim it's the volume that causes the water level to rise? Or do you claim it's the weight? And what is your evidence (from the class data chart) that supports your claim? And what is your reasoning? How do you explain the results?
Curriculum-Concepts Chart (C-C) (n = 1)	Common across three grades; summarizes how understandings of a network of key concepts are built in each grade unit (3-5) and across three grade units; presented separately from lesson plans	The target understanding of the concept of weight in Grade 3 is: *The weight of objects can be compared using a pan balance and standard (gram) weights*. The target understanding expands to include the following in Grade 4: *The weight of solids and/or liquids can be compared using a digital scale and can be represented on a weight line or a table.*

Curriculum-Overview (C-O) (n = 3)	The "Curriculum at a Glance" table summarizes learning activities of investigations in a grade-level unit; shows how activities in different sections within a unit build students' understandings; presented separately from lesson plans	An example from the Grade 3 table features an investigation question, learning goals and activities. How good are our senses at comparing the weight of cubes? Order the material cubes by felt weight. Create need for a measurement and introduce the pan balance.
Curriculum-Narratives (C-N) (n = 69)	Provide overviews of learning goals and activities within a grade unit, clarifies how investigations build on one another. Content coherence presented at three levels: Unit Level (start of each unit), Section Level (start of each section comprising a series of investigations in a unit), Lesson Level (start of each investigation)	Overview of Grade 3 unit: *The first [section], Investigating Materials, helps students distinguish between objects and materials. The second [section], Investigating Weight, focuses on weight as a property of matter. Students make the transition from felt weight, perceived with their hands, to measured weight using a pan balance.* Section on Investigating Materials: By exploring the similarities and differences between materials, students begin to see why some materials are better suited for some objects than others. Students begin to distinguish objects by their properties with particular attention to weight and material. Lesson on Investigating Materials: Students likely encountered difficulty in their quest to order the cubes by felt weight. In this investigation, they get help from a scientific instrument: the pan balance. By the end of this investigation, students will better understand the limitations of felt weight and the value of instruments for careful measuring.
Assessment-Oral and Written (A-OW) (n = 35)	Formative assessments draw on students' thinking evidenced in whole class discussions, small group investigations, student notebooks and responses to written 'concept cartoons'; address both scientific concepts and inquiry practices; provide questions, criteria for	In a Grade 4 investigation on changes in weight and volume when a ball of clay is reshaped, prompts ask teachers to consider students' predictions, accuracy of measurements recorded in notebooks, students' use of data and reasoning; suggest using class data to discuss possible sources of error in measuring weight and volume.

	interpretation, suggested next steps; embedded in lesson plans	
Subject Matter-Scientist Essays (SM-SE) (n = 13)	Scientist's perspective clarifying nuances of target concepts and scientific practices; presented separately from lesson plans for each section of a grade unit, appear side-by-side with corresponding Child Essays	Excerpt from Grade 5 essay on evaporation and condensation: On the microscopic level we think of evaporation as a process in which an occasional molecule in the liquid (or solid) happens to get enough energy from random thermal motion to break its bonds to its neighbors and escape. It's not a collective phase transition, like melting, freezing, or boiling, so it happens at any temperature. Excerpt from Grade 4 essay on the importance of reasoning and evidence in science: There are really only two valid ways to support a scientific claim: empirical evidence and logical reasoning from well-established principles. In ordinary life, we rely on analogy, anecdote, higher authority, and on hunch and intuition. To be called "scientific" an explanation must rest on the twin pillars of reasoning and evidence. To offer an explanation in science is to claim that one phenomenon arises as a result of some other phenomenon or process. A good scientific explanation accounts for, or is at least consistent with, all the relevant evidence. Scientists often come up with tentative explanations (hypotheses) that account for one observation or a few, but then try to consider whether other facts contradict the hypothesis or are explained or clarified by it).
Subject Matter-Boxed Notes (SM-BN) (n = 32)	Elaborate the scientific concepts to be introduced to students; sometimes explain additional complexity beyond intended student understanding; embedded in lesson plans	Boxed note explaining the complexities of evaporation and condensation in a Grade 5 investigation: Condensation is related to both humidity and temperature difference. When air that includes water vapor is cooled to a lower temperature, the particles of water vapor draw closer together. If the air is sufficiently cooled, drops of condensation will form. Heat energy is necessary for evaporation to occur. Water can evaporate at very low temperatures, particularly when the humidity of the air is low.

The inductive analysis revealed that, about the nature of contributions, designers contributed proactively and reactively to various PCK components and educative features. Table 3.5 presents a synthesis of these contributions.

Table 3.5: Nature of designer contributions across phases.

		Design Process Phases								
		Analysis			Development			Evaluation		
	Designers' Disciplinary Backgrounds	CP	SE	P	CP	SE	P	CP	SE	P
PCK Components (and Educative Features)	Student thinking (child essays; boxed notes)	▓			▓	█		▓	▓	
	Instructional Strategies (boxed notes; consistent tripartite structure)		▓					▓	▓	
	Curriculum (concepts chart; overviews; narratives)	▓	▓	░	█	█			▓	
	Assessment (oral and written assessments)		▓		▓	▓				
	Subject Matter (scientist essays; boxed notes)					█	▓		▓	

Legend: CP = Cognitive Psychologist; SE = Science Educators; P = Physicist; See Table 3.4 for educative feature codes. Dark grey = proactive contributions; Light grey = reactive contributions; Black = both proactive and reactive contributions; White = no detailed data available/not applicable.

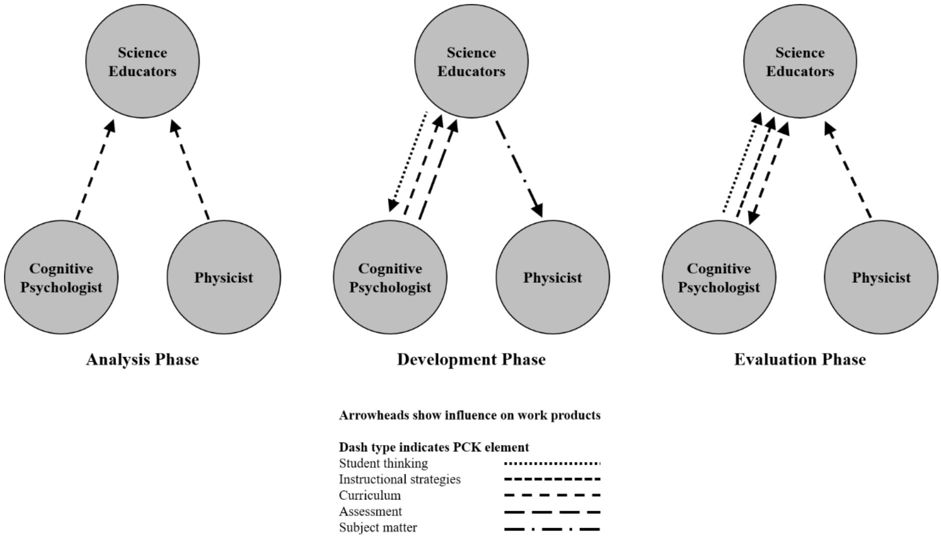


Figure 3.1: Intermeshing of designer contributions across design process phases and in relation to PCK components.

There was also intermeshing of designer contributions. A synthesis of the intermeshing interactions across the design process phases and in relation to the PCK components is depicted in Figure 3.1. The circles depict the three areas of designer expertise and the arrows indicate the contribution of inputs from designers of one expertise area to those of another area towards creating educative features. The direction of the arrows indicates the flow of proactive and/or reactive inputs for designing specific educative features. By depicting the expertise areas and the flow of inputs between them, the figure provides at once a view of the whole team contributions and those of designers from individual expertise areas towards various PCK components across phases of the design process.

The design process phases are used to organize the remainder of the findings in this section.

3.4.1 Analysis phase

3.4.1.1 Student thinking

The *cognitive psychologist* (P5) had previously co-authored a white paper describing a hypothetical learning progression for matter, containing research-based insights into young children's common conceptions and misconceptions about matter and the role of instruction in developing their understanding. P5's prior research was an important proactive contribution to help the design team understand children's ideas and to later develop the child essays (ST-CE).

3.4.1.2 Instructional strategies

The *science educators* contributed proactively by crafting a vision of teaching science through inquiry to include in the grant proposal. They were also aware that primary school teachers may be unfamiliar with science inquiry practices; therefore, teachers would need scaffolding in order to pose questions pertinent to both the science discipline and students' interests; to help students develop testable predictions; to guide students' observations during investigations; and to interpret evidence and articulate ideas through argumentation. This vision was later formalized in the consistent tripartite structure (IS-CTS) during evaluation and redesign phases. As P2 recalled during the interview,

> *We came up with this [lesson] structure of what we thought [scientific practices] looked like in investigations, that was going to be repeated again and again, that we have that framework of ask the question, do an investigation, and then do the make meaning discussion. And so that had to do with our deep sense of how you could really engage in [scientific] practices. It was the way that we understood [scientific] inquiry, and it was something that we really lived, that we really did that for all those activities.*

3.4.1.3 Curriculum

Designer contributions were intermeshed and designers with different backgrounds contributed both proactively and reactively in supporting this component. First, the *cognitive psychologist's* (P5) white paper mentioned before, which detailed a research-based, hypothetical learning progression on matter for primary and secondary school students, provided the science educators with the first roadmap for the present curriculum's goals and conceptual focus. In proactively designing this component, the *science educators* outlined a sequence in the grant proposal, beginning with rocks and soil in Grade 3, and proceeding to liquids in Grade 4 and finally gases in Grade 5. Drawing on the prior research on learning progression and related in-house projects, they emphasized introducing the concepts through solid materials because these were more familiar, tangible and observable to students than liquids and gases. This sequence, manifested in the C-C, diverged from typical curricula on matter (involving short investigations of unrelated objects and examples of concepts) by supporting inquiry through a sustained six-week study at each grade level. Each proposed grade-level sequence also reflected the main conceptual focus of the hypothetical learning progression.

Second, the original learning progressions work by P5 had proposed versions of standards-based science ideas suitable to teach at broad grade ranges and suggested scientific practices for students in those grade ranges. For this curriculum, however, a finer-grained progression was needed to help the science educators craft curricular goals and conceptual foci for each of grades 3, 4 and 5. At the beginning of the curriculum project, the team brainstormed and refined the framework to undergird the science educators' work for developing the present curriculum and to guide P5's work on the associated research for this curriculum. P5 prepared a more detailed map of conceptual understandings for each grade within the 3-5 range to help the science educators later develop separate grade level units. This output crystallized into the science concepts chart (C-C) to support teachers' understanding of the curricular goals.

Furthermore, while designing the Grade 5 unit, the team revisited the underlying framework to identify which of two parallel directions to pursue: the concept of density or that of phase change, where density as a concept was included but the emphasis was on understanding gases as a phase of matter. Whereas the cognitive psychologist advocated starting from density, the science educators argued for focusing on phase change, considering students' prior knowledge of mathematics, alignment with the schools' science curriculum and standards, and limited implementation time. This was indeed a crucial point in the design process, and the team finally chose the phase change direction. The following interview quotes from science educators P1 and P2 respectively highlight the team's dilemma, negotiation of different perspectives, and their rationale:

> *The hypothetical [learning] progression addressed both [density and phase change]. But we began to realize within the scope of the curriculum. we couldn't address both of those. One of the things that we saw when we made the decision to focus on phase change and transformations in 5th grade, as opposed to density, was that students just didn't have the mathematics to do an in-depth study of density in the 5th grade.*

> *There is a trade-off between the cognitive psychologist's idea about how [children's] ideas develop, and the scientist's idea about, what are big, important ideas [in science]? And maybe just the realities of the classroom, like how much*

> *time do you have here? A whole lot of the standards to do with weight, volume, and density, are in math, not in science. You begin to realize that if this is something that's an important science concept when you're thinking about matter, you have to squeeze it in to so few hours in the week to get that in.*

To resolve this dilemma, the *physicist* (P6) contributed reactively by clarifying what was important to teach from a disciplinary perspective. He identified salient science ideas in each strand and explained how the strands related to previous grade units and to the schools' curricular goals. He also reiterated addressing the big science idea that gases are a form of matter because it prefigured the particulate model, which was the ultimate student learning goal of the present curriculum. His input was reflected in the C-C. Here is how P6 summarized his perspective:

> *[The density direction] didn't match at all the [science] standards and the curriculum in the actual school. And the other major problem I recall we ran into was that all the stuff that we'd wanted to begin with about measurement and standard units and comparing quantities, and even volume - those were all topics that were under the mathematics curriculum in the schools. Another issue was that [the schools'] curriculum in [fifth] grade focused heavily on the water cycle. You can't understand the water cycle if you don't understand that gases are matter. From my point of view, sort of an overarching goal of this was really to prepare students to be ready to talk about atoms and molecules in middle school. And it seemed really important to me to be able to get there, that you needed to understand that gases are matter. Because usually, the first place you want to talk about atoms and molecules is in the context of gases. You can't do that if you don't already believe that gases are something.*

Reflecting on the team's decision, P5 stressed its collaborative nature:

> *That shows you the value of how closely we worked together and thought about these. It's not like [science educators and physicist] were saying [density direction] was unimportant. I think we agreed these [directions] are not necessarily either or, but they only had time for one. We all agreed this seemed like a good way to go. It wasn't where we were envisioning going, necessarily, at the start, as [cognitive psychology] researchers.*

3.4.1.4 Assessment

Drawing on their own prior work, the *science educators* emphasized formative assessments in the grant proposal as a core component of the proposed curriculum. In producing this output, they proposed embedding assessments into students' learning activities (as opposed to providing teachers with a separate set of instruments); in so doing, they stressed assessments about both science content and inquiry practices. Finally, they proposed collecting student work during curriculum implementation to build developmental criteria for the learning progression, and to create systematic and less teacher-subjective assessments.

PCK Components	**Designers**	**Nature of contributions**	
Specific output	*Disciplinary Background*	*Proactive*	*Reactive*
Student Thinking *Child Essays*	Cognitive Psychologist	Prior research describing students' typical thinking	NA
Instructional Strategies *Consistent Tripartite Structure*	Science Educators	Crafted vision in grant proposal for structuring inquiry-based lessons	NA
Curriculum *Concepts Chart*	Cognitive Psychologist ↓	White paper on hypothetical learning progression; detailed map of grade-level learning progression; feedback on emphasizing density over phase change in learning progression framework for Grade 5 unit design	NA
	Science Educators ↑	Crafted vision in grant proposal for sequence of conceptual understanding; feedback on emphasizing phase change over density in learning progression framework for Grade 5 unit design	NA
	Physicist	NA	Clarified rationale for emphasizing phase change over density in learning progression for Grade 5 unit design
	Whole Team	NA	Brainstormed, refined detailed, grade-level learning progressions framework
Assessment *Oral and Written Assessments*	Science Educators	Crafted vision in grant proposal for embedding formative assessments in student learning activities	NA

Figure 3.2: Nature of contributions and intermeshing in the analysis phase.

To summarize, during the analysis phase, designers contributed in various ways to the PCK components of student thinking, instructional strategies, curriculum, and assessment. The proactive contributions included preliminary ideas to craft their vision, and the reactive contributions included consideration of possible science content for the curriculum. Finally, designer contributions were intermeshed for the curriculum component, as the cognitive psychologist's prior work and feedback on learning and the physicist's clarification of science content to emphasize guided the educators' work on subsequent unit development (see Figure 3.2). [6]

3.4.2 *Development*

3.4.2.1 Student thinking

From a conceptual change perspective, the *cognitive psychologist* (P5) contributed proactively by explaining how children may hold initial and/or alternative

---

[6] The up and down arrows in Figures 3.2, 3.3, and 3.4 indicate intermeshing of designer contributions.

conceptions and experience difficulties with specific concepts related to matter. These explanations manifested in the child essays (ST-CE). Designer contributions were intermeshed as P5 created this output based on proactive input provided by science educators P2 and P4, identifying key scientific ideas for teachers' background knowledge. Further, *science* educator P1 provided reactive input through feedback on language and clarity to help revise the essays.

3.4.2.2 Curriculum

Designer contributions were intermeshed as the *cognitive psychologist* (P5) stressed a learning progressions perspective, which focused on the child's network of concepts and beliefs (as opposed to the experts'). Her proactive input involved identifying intermediate steps as targets to move children's understanding forward instead of destabilizing it. As P5 explained,

> *Your goal in a curriculum is to move the network [of concepts] forward, transforming it without destabilizing it. So a lot of traditional science instruction tries to define learning goals by the expert understanding. Let's break it into little pieces. And a learning progression's approach says that's not how you define the goals. The expert pieces are in terms of concepts that are miles away from where the kids are. You have to think much more creatively about it, and imagine intermediate steps that are targets, that are in terms of their own network of concepts, that aren't going to just match it but are moving it forward.*

P5 also offered reactive input by critiquing written plans of grade-level units developed by the *science educators*. In so doing, she attended to the conceptual foci, learning activities, and anticipated issues and strategies in students' learning. The *cognitive psychologist's* contributions were manifested in the science concepts chart (C-C) and the curriculum overviews (C-O).

The *science educators'* contributions were manifested in educative features C-C, C-O, and the curriculum narratives (C-N). With respect to proactive contributions, they developed grids describing sequences of concepts and learning activities for grade-level units, aligned with the learning progression framework. They used the grids to also envision conceptual build across the grades. Further, working reactively in critiquing drafts of lesson plans, the *science educators* drew on their primary school teaching experience and their background in science and engineering. They considered target grade-level students' capacities, shedding light on what was reasonable to expect for activities like writing or manipulating materials. From a scientific perspective, the *science educators* pondered suitable approaches for developing science ideas within short timeframes of single lessons or sequences of lessons. They also critiqued the drafts with a focus on how key scientific ideas and inquiry practices may be integrated and played out during classroom enactment. P3 and P4 respectively described the *science educators'* contributions thus:

> *So plotting out target understandings and brainstorming possible activities, things that we knew that kids of that age could do, and then really brainstorming*

> *the content sequences it might possibly build, making sure that there always was this little grid of the progression and some of the ideas that seemed essential to be included. And then [P4] would bring his drafts to the meeting and we would go over them and critique them, and make suggestions. I think that one of my roles was that I had a lot of experience in the classroom at that age level. So I knew what kids typically could and couldn't do when they were 8 years old or 9 years old or 10 years old, so I had a pretty good sense of what was reasonable to expect in terms of, for example, manipulating materials or writing. And then P2 would often take what had been done and put it into some kind of a grid, more of a conceptual chart.*
>
> *P2 would say, do you think doing these two [lessons] first is better, or do you think doing this first and then doing that—and then she'd say why she thought that was a better approach for the science, the development of the science idea.*

3.4.2.3 Assessment

Designer contributions were intermeshed as the *cognitive psychologist* (P5) worked with science educators to develop 'concept cartoons' - a type of written formative assessment (A-OW) in which students respond to scenarios and alternative ideas about scientific concepts presented in cartoon-style drawings (Keogh & Naylor, 1999). The cartoons depict characters debating different explanations of scientific phenomena. One character's explanation is consistent with the scientific perspective, whereas other explanations reflect children' common understanding or confusions. Students are prompted to respond to each character's explanation. See the following excerpt from an external evaluation report of the Grade 4 unit:

> *One of the strengths [of the curriculum design process] identified by [the designers] was the inter-connectedness among team members. This resulted in several collaborations across fields of expertise. For example, a collaboration between one of the cognitive [psychologists] and a [science educator] resulted in innovative curriculum-embedded assessment items: Concept Cartoons that became an integral part of the [Grade 4 unit] and that will presumably continue into the [Grade 5 unit]. These assessments were particularly well-received by the [Grade 4] class teachers.*

To develop the concept cartoons, P5 contributed proactive input based on research on children's thinking, as described in this interview quote:

> *The concept cartoons were a place of meeting a need for formative assessment in the classroom using [learning progressions/conceptual change] research, what we found to have the alternative [cartoon character] responses be things that kids might find - things that a teacher might not think that the kids would think, but we could put them in, that would be things [students] would go for in a big way, and that would then therefore generate an interesting class discussion.*

Regarding proactive work by the *science educators*, P3 recalled, based on a review of existing formative assessment frameworks (e.g., Harlen, 2006), that they highlighted learning goals, varied sources of evidence of students' thinking, specific criteria for interpreting students' thinking, and identification of next steps to attain the goals. They mined project resources like videos of classroom enactment to exemplify oral assessments of students' discussions and investigations and excerpts from students' notebooks to exemplify authentic written work. Additionally, as evidenced in external evaluation reports, proactive tasks by the *science educators* included gathering feedback from field test teachers during monthly PD meetings to develop assessment criteria for interpreting students' thinking. They prepared and revised drafts of the assessments based on the team's feedback.

3.4.2.4 Subject matter

Designer contributions were intermeshed in supporting this PCK component. The *physicist* (P6) contributed proactively by explaining why concepts and scientific practices about matter were important to the discipline and explicated a rationale for teaching those to their students. The explanations were manifested in the scientist essays (SM-SE). P6 developed this output based on proactive input provided by *science educators* P2 and P4, identifying key scientific ideas for teachers' background knowledge. The essays were revised following reactive feedback about clarity and elaboration from *science educator* P1. As P6 described:

> *[P1] wanted from me a statement about why do scientists care about matter? Why is this something that we're hammering into our students? No one ever tells them where it's going, why science invented this idea and why we're hammering it on them. From the perspective of someone who's been through the whole thing and uses these ideas, but written, hopefully, in a way that would make sense to people who were not scientists but are engaging with the same materials. So the first thing I would have to do is to really think about it, and come up with an answer that satisfied me about why is it scientifically an important concept.*

To summarize, during the development phase, designers contributed to the PCK components of student thinking, curriculum, assessment, and subject matter. The proactive contributions included identifying target concepts, preparing sequences of concepts and activities, and reviewing existing frameworks. The reactive contributions included providing feedback on drafts of child and scientist essays to improve clarity. Finally, intermeshing was noted in all four components, with the science educators contributing both proactively and reactively to shape the essay outputs produced respectively by the cognitive psychologist and scientist, and the cognitive psychologist contributing proactively to shape the curriculum and assessment outputs produced by the science educators (see Figure 3.3).

3.4.3 Evaluation and redesign

3.4.3.1 Student thinking

Proactive contributions from the *cognitive psychologist* (P5) involved conducting clinical interviews for research to iteratively inform the curriculum design, based on the underlying learning progressions framework. Specifically, the interviews examined students' conceptual understandings during field tests of the curriculum enactment. Designer contributions were also intermeshed as the results about student understandings were communicated to the science educators to provide insights into strengths and limitations of their understandings of target concepts. For example, in revising the Grade 3 unit, P5 pointed out that students erroneously believed light material cubes were hollow inside compared to heavy material cubes. This finding was subsequently represented in a boxed note (ST-BN) for a Grade 3 investigation, stating, "students commonly think wood or plastic cubes are light because they are hollow inside. While sometimes objects are hollow or filled with other materials, it is not true in this case."

PCK Components	**Designers**	**Nature of contributions**	
Specific output	*Disciplinary Background*	*Proactive*	*Reactive*
Student Thinking *Child Essays*	Science Educators ↓	Identified key ideas to address in child essays	Provided feedback on language, clarity of child essays
	Cognitive Psychologist	Explained in child essays children's typical conceptions, difficulties	NA
Curriculum *Concepts Chart; Narratives; Overviews*	Cognitive Psychologist ↓	Identified intermediate conceptual understandings to target in learning progression	Provided feedback about conceptual focus, learning activities, student learning in grade-level unit plans
	Science Educators	Prepared grids for concept sequences, grade-level learning activities, cross-grade unit planning	Provided feedback on children's capacities, supporting scientific ideas, inquiry practices in lesson plans
Assessment *Oral and Written assessments*	Cognitive Psychologist ↓	Identified children's alternative conceptions for Concept Cartoons	NA
	Science Educators	Reviewed formative assessment frameworks; identified learning goals, student ideas, criteria, next steps, examples; gathered feedback on assessment criteria from field test teachers	NA
Subject Matter *Scientist Essays*	Science Educators ↓	Identified key ideas to address in scientist essays	Provided feedback on clarity, elaboration in scientist essays
	Physicist	Explained in scientist essays importance of target concepts, practices to science discipline, rationale for teaching those	NA

Figure 3.3: Nature of contributions and intermeshing in the development phase.

3.4.3.2 Instructional strategies

The *cognitive psychologist's* (P5) proactive input about students' conceptual understanding based on the curriculum field tests helped the science educators create tips for teachers to address alternative conceptions. These contributions were represented in boxed notes on instructional strategies (IS-BN) embedded in lesson plans, thus indicating the intermeshing of designer tasks. For example, P5 noted:

> *We gave [science educators] feedback on what we were seeing in the interviews, which suggests students didn't really understand volume too much in grade 3. And so we would bring up issues that [science educators] would focus on, and then the kids made a lot of progress with volume. We told them a lot of [students] think it's hollow in some of those light [cubes of different materials used in curriculum activity]. [The science educators] added to the curriculum cuts of [the cubes] just so they could show the kids that.*

Based on this feedback, a boxed note was added to a Grade 3 investigation on sorting same sized cubes of different materials, suggesting that teachers "explain that each cube is made of just one material and is solid all the way through."

The *science educators* contributed proactively by observing classroom testing and stressing the need to reinforce classroom discussions with a consistent structure to support teachers' enactment. Consequently, they crafted discussion supports such as questions to elicit and respond to students' predictions and explanations. These contributions were manifested in the consistent tripartite structure (IS-CTS). Additionally, they emphasized the need to provide explicit guidance for enacting scientific practices like constructing, communicating with, and revising explanatory models. To this end, the *science educators* designed tips which were manifested in boxed notes (IS-BN). For example, the notes provide tips for different lines of questioning and conceptual focus for explanatory models. As evidenced in a *science educator's* written observations, key insights included:

> *The teacher needs more guidance [for] reviewing [explanatory models], selecting a pair for students to analyze, and helping move the conversation forward in the class the next day as students review and discuss the selected models. When [students] commented on what they thought of the 2 models, how they compared, most of their observations were about how to improve the drawing and not how to improve the model. They just need more experience, and teacher needs more guidance. I had shared with [pilot teacher] the two lines of questioning: clarification questions and evaluative questions. We'll need to provide examples of each. Teachers will not be in a position to ask such questions when they have so little experience with them themselves.*

3.4.3.3 Curriculum

Through a series of evaluation and redesign measures taken proactively by the *science educators*, sequences of concepts and instructional activities were formalized and materialized finally in the curriculum overview table (C-O) and narratives (C-N). Specifically, based on early trials of activities with children that were conducted at their workplace, the *science educators* generated unit outlines of student investigations, goals, and key ideas for classroom discussions at specific grade-levels. The whole team provided reactive input by critiquing the outlines with an eye on how the goals and activities served the underlying learning progressions framework, thus intermeshing their contributions. As indicated in an external evaluation report, “finally, after about two months of intense discussion, a consensual agreement on the outline would be reached.” During this process, “the learning progression was central to [the team’s] conversations about the evolving curriculum”. See this excerpt from the evaluation report:

> *[The learning progression] was part of all the conversations, no one lost sight of where we all wanted to get to. So when we were talking about activities, we would ask ourselves, “What does this have to do with the [learning progression]?” There was a real effort to lay out charts of each unit and to state for each lesson, “What’s the learning goal?” And all the learning goals were aimed towards the progression.*

Based on the agreed upon outlines, proactive work by the science educators included preparing lesson plans with learning goals and structure for investigations and ‘Make Meaning’ discussions. The lesson plans were revised following observations of classroom testing. Additionally, the science educators provided feedback to revise the detailed (hypothetical) learning progressions framework created originally by the cognitive psychologist into an “as enacted” framework (and manifested later in science concepts chart C-C), balancing theoretical considerations with practical needs and constraints. As described in an external evaluation report, the science educators strove to not only produce “a curriculum that maintained the integrity of the [learning progressions] framework, but also one that met the needs of the participating schools,” specifically of “teachers in [a statewide standardized assessment] world who don’t do hands-on science and don’t have a science background.” See this interview quote from *science educator* P1:

> *It was certainly that the learning progression was guiding the initial development of the curriculum. When we would make revisions, we were trying to hold onto that, always, but we were also thinking about – is this viable for students, and is it viable for teachers? And we were also saying – is this giving students the ideas that the cognitive [psychologists] were hoping for?*

3.4.3.4 Subject matter

Proactive work from the science educators involved observing classroom enactment to redesign supports for particular scientific concepts in the teacher materials. For example, during pilot testing of Grade 5 investigations on water freezing and melting, they noted that the curriculum materials did not clarify to teachers why water expands when frozen nor that this expansion is anomalous compared to other liquid materials. These insights were ultimately manifested in boxed notes (SM-BN) embedded in the revised lesson plans. One note provides a basic explanation for the increased volume of frozen water: In simplest terms, the tiny water particles rearrange themselves to form crystals when they freeze. In their new arrangement, the particles are not as tightly packed together as they are in liquid form and they take up more space.

To summarize, during the evaluation and redesign phase, the designers contributed in various ways to the PCK components of student thinking, instructional strategies, curriculum, and subject matter. The proactive contributions included observing classroom enactment and examining student conceptions through pilot and field tests of the curriculum implementation to inform redesign of supports for student thinking, instructional strategies, and subject matter. The reactive contributions were in the form of feedback on the unit outlines. Finally, intermeshing was noted for the components of student thinking, instructional strategies, and curriculum, as input from field testing by the cognitive psychologist informed additional supports, and the cognitive psychologist and the physicist gave feedback on the unit outlines created by the science educators (see Figure 3.4).

PCK Components	**Designers**	**Nature of contributions**	
Specific output	*Disciplinary Background*	*Proactive*	*Reactive*
Student Thinking *Boxed Notes*	Cognitive Psychologist ↓	Examined progress in students' understandings during field tests; communicated findings to science educators	NA
	Science Educators	Created boxed notes in lesson plans for anticipating students' typical conceptions	NA
Instructional Strategies *Consistent Tripartite Structure; Boxed Notes*	Cognitive Psychologist ↓	Examined progress in students' understandings during field tests; communicated findings to science educators	NA
	Science Educators	Observed classroom testing; refined structure, supports for enacting inquiry; created boxed notes in lesson plans for addressing students' typical conceptions, enacting scientific practices	NA
Curriculum Concepts Chart, Overviews, Narratives	Science Educators ↕ ↑	Conducted early trials at workplace; observed classroom testing; prepared, revised unit outlines, lesson plans; proposed revisions to underlying learning progressions framework	NA
	Cognitive Psychologist Physicist	NA	Feedback on learning goals, activities in unit outlines
Subject Matter *Boxed Notes*	Science Educators	Observed classroom testing; created boxed notes in lesson plans to clarify concepts	NA

Figure 3.4: Nature of contributions and intermeshing in the evaluation and redesign phase.

3.5 Discussion

3.5.1 Reflections on the findings and substantive recommendations

This section presents reflections on the main findings of the study in light of relevant literature on interdisciplinary collaboration, PCK, and educative materials. In addition, distilled from both the findings and literature are recommendations for both research and practice related to collaborative interdisciplinary design to support teachers' PCK and thereby support instruction. Whereas the recommendations emerged from the case of a primary school science curriculum, several implications for designing curricula and instruction seem relevant to other school levels and subject areas.

First, with respect to the nature of designer contributions, the proactive and reactive nature of contributions observed in this study shed light on how different designer expertise can contribute to shaping various educative features over time. This is a notable finding because these kinds of contributions can help members of interdisciplinary teams to systematically offer unique inputs consonant with their areas of expertise (Wang, 2014). Indeed, for complex endeavors (as exemplified in the present case of creating longitudinal curricula containing many educative features), the requisite and pertinent knowledge to craft solutions does not lie within the contributions of a single designer but is distributed among the inputs of different designers (Arias et al., 2000). Both proactive and reactive contributions from varied expertise can thus help design teams to attain goals efficiently that cannot be attained through the efforts of individual professionals alone (Bronstein, 2003; Bruner, 1991). A recommendation then for future research is to map in greater detail the nature of contributions from designers with different expertise for specific PCK components or to understand how designers with differing expertise can work within diverse groups during each phase of design (analysis, development, and evaluation). For instance, what is the role of subject matter experts when designing supports for PCK of instructional strategies or assessments and how can their proactive and reactive contributions shape the designed product? Based on this insight, interdisciplinary design teams can plan for what kinds of proactive and reactive inputs to draw out from its members according to PCK components as well as consistently during different design phases.

Another key finding of this study is that of intermeshing of designer contributions for all PCK components and during different design process phases to coordinate inputs from different areas of expertise and yield coherent educative materials. Thus, not only were the different outputs (educative features) brought together to produce a unified curriculum, but the outputs themselves resulted from varied designer expertise. The interplay of disciplinary inputs is important because while designers may bring specialized disciplinary perspectives to a design task, insights and solutions emerge from communication and integration of different perspectives (Wang, 2014). The intermeshing for specific design tasks may help designers take advantage of the available expertise to generate innovative solutions (Barber, 2015). This is especially critical to foster interdependence and mutual respect for productive interdisciplinary collaboration as they pursue shared goals (Bronstein, 2003).

Additionally, with respect to intermeshing, the inductive findings show how collaboratively created artifacts, such as the detailed learning progressions framework, underpinned the designers' negotiation of the focal science content and their critiques on drafts of the written curriculum. The literature on collaborative interdisciplinary design stresses the role of *boundary objects* – shared design artifacts – which externalize designers' ideas and facilitate reflection and communication (Flood et al., 2015). Boundary objects are especially crucial to build shared understanding among designers working together as a *community of interest* to address problems of shared concern (Fischer & Ostwald, 2005), as instantiated in the present design team composed of science educators, practicing scientists and cognitive psychologists. Whereas this study shows how a curriculum framework served as a boundary object for the PCK component of curriculum, additional research is needed to investigate how various other boundary objects may contribute to intermeshing of designer interactions for supporting other PCK components. Based on this insight, design teams can plan on incorporating different boundary objects, such as documents of prototypes, to facilitate intermeshing of designer contributions towards shared design tasks.

The findings about intermeshing extend other research on collaborative design. Prior work on collaboration of expert designers has highlighted processes such as negotiation of task-specific aspects and interactive evaluation of the outcomes (Kvan, Vera, & West, 1997). Studies have also described social processes in design teams and tactics by which designers analyze problems and develop solutions. For example, designers are found to externalize their understanding of design requirements and specifications, and co-operatively add to and refine initial design ideas (Cross & Cross, 1995). And yet other research has examined the development of shared understanding in design teams, pointing to dynamic patterns in designer focus on the taskwork (i.e., the intended product), the teamwork (i.e., the underlying design process), and specific actions to perform (Cash, Dekoninck, & Ahmed-Kristensen, 2020). Whereas the literature has described these general processes in design teams, the concept of intermeshing provides an analytical lens to unpack and further develop a more fine--grained understanding of the ways in which individual designers contribute, enable, or specify the emergent team work based on their respective expertise during these collaborative design processes.

In addition, the study shows how this mix of various disciplinary inputs throughout phases of the design process helps designers to systematically and iteratively target multiple PCK components in tandem. This is important because the components are interconnected (Magnusson et al., 1999; Park & Chen, 2012); hence, addressing them singly may not be ideal in supporting teacher learning. This designer work is consistent with existing heuristics (Davis & Krajcik, 2005) and principles (Davis et al., 2017) in suggesting the importance of designing to support teachers' PCK in multiple ways, and with recent examples of such materials (Arias et al., 2016; Roseman et al., 2017; Schneider, 2013). Finally, designer work focused on helping teachers understand curricular content and plan for their teaching (e.g., the child and scientist essays and curriculum narratives and overviews to aid background knowledge of curricular content and organization), as well as to enact their plans in-the-moment of classroom instruction (e.g., boxed notes, consistent tripartite structure including specific language and questions, and oral and written formative assessments). This dual attention is vital because teachers draw on their PCK to plan and reflect on their teaching as well as during enactment (Kirschner et al., 2016), with recent research showing that the PCK held by teachers affects their instructional actions in the moment-of-teaching, i.e., enacted PCK (Kuglemeyer et al., 2020).

3.5.2 Limitations and methodological recommendations

This study involved a retrospective analysis of designer interactions. Related to this approach, three important limitations bear mention. First, the choice to identify a project with successful outcomes meant identifying a project that had been completed long enough for the outcomes to be measured. Given the elapsed time, and the fact that the study relied on participants' memories for describing their design process and interdisciplinary contributions, detailed descriptions were not always possible. Although project documents were used to extract additional information and support respondent recall, some details were challenging to obtain and did not lend themselves to in-depth scrutiny or were excluded from the data analysis. For example, monthly PD meetings and co-teaching the curriculum with field test teachers were important measures taken by the science educators. However, precise details of how these measures shaped various educative supports were lacking.

A second limitation stems from the first. Namely, whereas the inductive analysis revealed the nature and intermeshing of designer contributions for some PCK components in each design phase, a comprehensive overview was not feasible. For example, the data set did not yield adequate information on designer expertise and inputs in supporting teacher knowledge of instructional strategies during the development phase or in supporting knowledge of assessments in the evaluation (and redesign) phase. Furthermore, a similar point may be noted in Figure 3.1 depicting intermeshing of designer contributions for different PCK components across design process phases. Specifically, the presence of unidirectional arrows (indicating the flow of proactive and/or reactive contributions) between specific areas of expertise for some PCK components suggests a basic coordination of independently crafted inputs, instead of a process involving back-and-forth and discussions between designers or the team as a whole to yield a more synergistic output (akin to the outputs for the PCK component of curriculum). For example, considering the learning progressions framework underpinning the design work, one could reasonably expect that for the PCK components of student thinking and assessment, there was substantial discussion between the cognitive psychologist and science educators about which student difficulties and alternative conceptions to address and how in the associated educative features (e.g., child essays and concept cartoons). While it is clear that such interactions were limited in our data set, we cannot rule out the possibility that this was a kind of false negative, due to the retrospective nature of the study.

Hence, further verification of such details should be a priority in future research, given that recent reforms (National Academies of Science, Engineering and

Medicine, 2017) and research in teacher professional learning (Furtak et al., 2016) emphasize formative assessments. The (science) education community would benefit from knowledge of design processes behind such assessments. We therefore recommend future research on the design processes of ongoing curriculum projects which may enable researchers to collect observations, documentation, and interview data at regular time points, thus relying less on participants' memories.

The third limitation is the study's ability to unpack whether or how the nature and amount of designer contributions might have been influenced by the number of hours worked and/or the number of designers who composed the 'sub-teams' of science educators, cognitive psychology researchers, and science experts. The present data were gathered from a subset of the full project team, and contained only partial information on the time devoted to this project by the designers. Whereas one might reasonably expect the science educators to have devoted the most time to this work, considering their relevant expertise in science curriculum design, primary school teaching, and teacher PD, future research could systematically collect data to examine designer contributions in relation to the size of the sub-teams and the length of time of work.

3.5.3 *Significance of the study*

In closing, this study brings into high relief the painstaking nature of interdisciplinary collaboration during design to produce beneficial supports for teachers and students. Such supports are crucial for enabling teachers to fine-tune learning environments and instructional approaches in ways that engender positive learner outcomes (Pareja Roblin et al., 2018). Furthermore, as evidenced in recent research, educative materials help teachers shape instruction to engage students with important content and practices (e.g., Arias et al., 2016). But high-quality curriculum design is an expensive undertaking and requires significant and sustained funding from various agencies (Burkhardt & Schoenfeld, 2003). To aid these endeavors, the study contributes a detailed design case to help other designers learn from precedents, describing both the designed product and the underlying designer rationales and activities (Howard, Boling, Rowland, & Smith, 2012). Moreover, this study yields detailed theoretical insights into collaborative, interdisciplinary design processes, revealing how designers make specialized, discipline-specific contributions, and coordinate varied inputs to systematically shape coherent educative materials. Finally, the study also offers practical recommendations to guide designers engaging in collaborative interdisciplinary design of curriculum materials. The recommendations can serve experienced and novice designers in different educational contexts as well as interdisciplinary educational design teams.

References

Arias, A. M., Bismack, A. S., Davis, E. A., & Palincsar, A. S. (2016). Interacting with a suite of educative features: Elementary science teachers' use of educative curriculum materials. *Journal of Research in Science Teaching*, 53(3), 422-449.

Arias, E., Eden, H., Fischer, G., Gorman, A., & Scharff, E. (2000). Transcending the individual human mind—creating shared understanding through collaborative design. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *7*(1), 84-113.

Barber, J. (2015). How to design for breakthrough. *Educational Designer*, 2(8). Available online at: https://www.educationaldesigner.org/ed/volume2/issue8/article29/ (Accessed 20 October 2018).

Beyer, C. J., Delgado, C., Davis, E. A., & Krajcik, J. (2009). Investigating teacher learning supports in high school biology curricular programs to inform the design of educative curriculum materials. *Journal of Research in Science Teaching*, 46(9), 977-998.

Bismack, A. S., Arias, A. M., Davis, E. A., & Palinscar, A. S. (2015). Examining student work for teacher uptake of educative curriculum materials. *Journal of Research in Science Teaching*, 52(6), 816-846.

Bronstein, L. R. (2003). A model for interdiscplinary collaboration. *Social Work*, 48(3), 297-306.

Bruner, C. (1991). Ten questions and answers to help policy makers improve children's services. Washington, DC: Education and Human Services Consortium.

Cash, P., Dekoninck, E., & Ahmed-Kristensen, S. (2020). Work with the beat: How dynamic patterns in team processes effect shared understanding. *Design Studies*, 69.

Cervetti, G. N., Kulikowich, J. M., & Bravo, M. A. (2015). The effects of educative curriculum materials on teachers' use of instructional strategies for English language learners in science and on student learning. *Contemporary Educational Psychology*, 40, 86-98.

Clarke, D., & Hollingsworth, H. (2002). Elaborating a model of teacher professional growth. *Teaching and Teacher Education*, 18(8), 947-967.

Cochran, K. F., De Ruiter, J. A., & King, R. A. (1993). Pedagogical content knowing: An integrative model for teacher preparation. Paper presented at the Annual Meeting of the *American Educational Research Association*, Chicago, IL, USA.

Cross, N., & Cross, A. C. (1995). Observations of teamwork and social processes in design. *Design Studies, 16*, 143-170.

Davis, E. A., & Krajcik, J. S. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher*, 34(3), 3–14.

Davis, E. A., Palincsar, A. S., Arias, A. M., Bismack, A. S., Marulis, A. M., & Iwashyna, S. K. (2014). Designing educative curriculum materials: A theoretically and empirically driven process. *Harvard Educational Review*, 84(1), 24–53.

Davis, E. A., Palincsar, A. S., Smith, P. S., Arias, A. M., & Kademian, S. M. (2017).

Educative curriculum materials: Uptake, impact, and implications for research and design. *Educational Researcher*, 46(6), 293-304.

Edelson, D. C. (2002). Design research: What we learn when we engage in design. *Journal of the Learning Sciences*, 11(1), 105–121.

Ertmer, P. A., & Quinn, J. (2007). *The ID case book: Case studies in instructional design* (3rd edition). New Jersey: Pearson.

Fischer, G., & Ostwald, J. (2005). Knowledge communication in design communities. In *Barriers and biases in computer-mediated knowledge communication* (pp. 213-242). Springer, Boston, MA.

Flood, V. J., Neff, M., & Abrahamson, D. (2015). *Boundary interactions: resolving interdisciplinary collaboration challenges using digitized embodied performances*. In T. Koschmann, P. Häkkinen, & P. Tchounikine (Eds.), Exploring the material conditions of learning: opportunities and challenges for CSCL, the Proceedings of the Computer Supported Collaborative Learning (CSCL) Conference (Vol. 1, pp. 94-101). Gothenburg, Sweden: ISLS.

Furtak, E. M., Kiemer, K., Circi, R. K., Swanson, R., de Lyon, V., Morrison, D., et al. (2016). Teachers' formative assessment abilities and their relationship to student learning: findings from a four-year intervention study. *Instructional Science*, 44(3), 267-291.

Gess-Newsome, J., Taylor, J. A., Carlson, J., Gardner, A. L., Wilson, C. D., & Stuhlsatz, M. A. (2017): Teacher pedagogical content knowledge, practice, and student achievement, *International Journal of Science Education*, DOI: 10.1080/09500693.2016.1265158

Grossman, P. L. (1990). *The making of a teacher: Teacher knowledge and teacher education*. Teachers College Press, Teachers College, Columbia University.

Guba, E. G. (1981). Criteria for assessing the trustworthiness of naturalistic inquiries. *Educational Communication and Technology*, 29(2), 75-91.

Gustafson, K. L., & Branch, R. M. (2002). What is instructional design? In R, A. Reiser & J. V. Dempsey (Eds.) *Trends and Issues in Instructional Design and Technology* (pp.16-25). Columbus: OH, Merrill Prentice Hall.

Harlen, W. (2006). *Teaching, learning and assessing science 5-12* (4th edition). London, UK: Sage Publications.

Hill, H. C., & Charalambous, C. Y. (2012). Teacher knowledge, curriculum materials, and quality of instruction: Lessons learned and open issues. *Journal of Curriculum Studies*, 44(4), 559-576.

Howard, C. D., Boling, E., Rowland, G., & Smith, K. M. (2012). Instructional design cases and why we need them. *Educational Technology*, 52(3), 34.

Keogh, B., & Naylor, S. (1999). Concept cartoons, teaching and learning in science: An evaluation. *International Journal of Science Education*, 21(4), 431-446.

Kind, V. (2009). Pedagogical content knowledge in science education: perspectives and potential for progress. *Studies in Science Education*, 45(2), 169-204.

Kirschner, S., Borowski, A., Fischer, H. E., Gess-Newsome, J., & von Aufschnaiter,

C. (2016). Developing and evaluating a paper-and-pencil test to assess components of physics teachers’ pedagogical content knowledge. *International Journal of Science Education*, 38(8), 1343-1372.

Krajcik, J., & Delen, I. (2017). The benefits and limitations of educative curriculum materials. *Journal of Science Teacher Education*, 28(1), 1-10.

Krajcik, J. S., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education*, 92(1), 1–32.

Kruse, R., Howes, E. V., Carlson, J., Roth, K., Bourdelat-Parks, B., Roseman, J. E., ... & Flanagan, J. C. (2013). Developing and Evaluating an Eighth Grade Curriculum Unit That Links Foundational Chemistry to Biological Growth: Changing the Research-Based Curriculum. Paper presented at the *NARST Annual International Conference*, Rio Grande, Puerto Rico, USA.

Kulgemeyer, C., Borowski, A., Buschhüter, D., Enkrott, P., Kempin, M., Reinhold, P., ... & Vogelsang, C. (2020). Professional knowledge affects action-related skills: The development of preservice physics teachers' explaining skills during a field experience. *Journal of Research in Science Teaching*.

Kvan, T., Vera, A., & West, R. (1997). Expert and situated actions in collaborative design. In P. Siriruchatapong, Z. Lin, & J.-P. Barthes (Eds.), Proceedings of 2nd International Workshop on CSCW in Design, 2nd International Workshop on CSCW in Design, International Academic Publishers, Beijing (pp. 400–405).

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teacher. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining Pedagogical Content Knowledge* (pp. 95–132). Dordrecht: Kluwer.

Marco-Bujosa, L. M., McNeill, K. L., González-Howard, M., & Loper, S. (2017). An exploration of teacher learning from an educative reform-oriented science curriculum: Case studies of teacher curriculum use. *Journal of Research in Science Teaching*, 54(2), 141-168.

Marks, R. (1990). Pedagogical content knowledge: From a mathematical case to a modified conception. *Journal of Teacher Education*, 41(3), 3–11.

Matuk, C. F., Linn, M. C., & Eylon, B. S. (2015). Technology to support teachers using evidence from student work to customize technology-enhanced inquiry units. *Instructional Science*, 43(2), 229 – 257.

McKenney, S. (2017). Een infrastructuur voor de professionele groei van docenten [Infrastructuring teacher professional growth]. *Inaugural lecture*. Enschede: University of Twente.

McKenney, S., & Reeves, T.C. (2012). *Conducting educational design research*. London: Routledge.

McNeill, K. L. (2009). Teachers' use of curriculum to support students in writing scientific arguments to explain phenomena. *Science Education*, 93(2), 233-268.

Merriam, S. B. (1988). *Case study research in education: A qualitative approach*. Jossey-Bass.

National Academies of Science, Engineering, and Medicine. (2017). *Seeing students learn science: Integrating assessment and instruction in the classroom.* Washington, DC: The National Academies Press.

Pareja Roblin, N., Schunn, C., Bernstein, D., & McKenney, S. (2018). Exploring shifts in the characteristics of US government-funded science curriculum materials and their (unintended) consequences. *Studies in Science Education, 54*(1), 1-39.

Park, S., & Chen, Y. C. (2012). Mapping out the integration of the components of pedagogical content knowledge (PCK): Examples from high school biology classrooms. *Journal of Research in Science Teaching*, 49(7), 922-941.

Park, S., & Oliver, S. J. (2008). Revisiting the conceptualisation of pedagogical content knowledge (PCK): PCK as a conceptual tool to understand teachers as professionals. *Research in Science Education*, 38(3), 261–284.

Roseman, J. E., Herrmann-Abell, C. F., & Koppal, M. (2017). Designing for the Next Generation Science Standards: Educative curriculum materials and measures of teacher knowledge. *Journal of Science Teacher Education*, 28(1), 111-141.

Schneider, R. M. (2013). Opportunities for teacher learning during enactment of inquiry science curriculum materials: Exploring the potential for teacher educative materials. *Journal of Science Teacher Education*, 24(2), 323-346.

Schneider, R. M., & Krajcik, J. (2002). Supporting science teacher learning: The role of educative curriculum materials. *Journal of Science Teacher Education*, 13(3), 221-245.

Shulman, L. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher*, 15(2), 4–14.

Smith, P. L., & Ragan, T. J. (1999). *Instructional Design (3rd edition)* (3rd editio). Hoboken, NJ: Wiley & Sons.

Songer, N. B. (2006). BioKids: An animated conversation on the development of curricular activity structures for inquiry science. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 355–369). New York: Cambridge University Press.

Taba, H. (1962). *Curriculum development: Theory and practice.* New York: Harcourt, Brace & World.

Tamir, P. (1988). Subject matter and related pedagogical knowledge in teacher education. *Teaching and Teacher Education*, 4(2), 99–110.

Thijs, A., & van den Akker, J. (2009). *Curriculum in development*. Enschede, The Netherlands: SLO Netherlands Institute for Curriculum Development.

Tobin, K., Tippins, D. J., & Gallard, A. J. (1994). Research on instructional strategies for teaching science. *Handbook of research on science teaching and learning*, 45-93.

Van Driel, J. H., Verloop, N., & De Vos, W. (1998). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching*, 35(6), 673-695.

Van Gog, T., Paas, F., & Merriënboer, J. J. (2004). Process-oriented worked examples: Improving transfer performance through enhanced understandings. *Instructional Science,* 32(1), 83–98.

Veal, W. R., & MaKinster, J. G. (1999). Pedagogical content knowledge taxonomies. *Electronic Journal of Science Education*, 3(4).

Wang, J. (2014). *Engineering Learning: Cross-Community Design, Development, and Implementation of Engineering Design Challenges at a Science Center*. Unpublished doctoral disseration, University of California, Berkeley.

Yin, R. K. (2014). *Case study research: Design and methods* (5th edition). Thousand Oaks, California: Sage Publications, Inc.

Chapter 4
Balancing Priorities

School-based citizen science can be a powerful means to engage youth in environmental education, yet developing robust science curricula around citizen science activities is tremendously challenging. Prior research provides limited examples and very little guidance for curriculum designers. To support the designers of school-based citizen science curricula, this research article presents a participant-observation case study of designer thinking and processes in creating and integrating in-class curriculum with citizen science fieldwork. Interviews, observations, and documents of designer work aimed at supporting middle school students' learning of climate change were analyzed to gain insight into designer thinking, challenges, and resolutions. Findings indicate how designer work evolved through various measures, including appraisal by external advisors, inspiring examples, surveys of teachers' implementations, and written pre-post assessments of student learning throughout the phases of analysis, development, and evaluation of the curriculum. Four key considerations for designing school-based citizen science curricula emerged from the data: creating the learning environment around the fieldwork; tackling concerns about data quality and utility; making scientist-designed fieldwork engaging to students; and balancing scientific and educational goals. These considerations are discussed in light of relevant literature, and educational implications for design and research are presented.

This chapter is based on:

Bopardikar, A., Bernstein, D., & McKenney, S. (2021). Designer considerations and processes in developing school-based citizen-science curricula for environmental education. *Journal of Biological Education*, 1-26.

Citizen science, defined as public participation in organized research efforts, engages the general public in partnering with professional scientists to study environmental change (Dickinson & Bonney, 2012). By collecting, submitting, and analyzing large quantities of data that are often beyond the resources of routine scientific projects, non-scientists can contribute significantly towards developing scientific knowledge of and solutions to problems faced by broader communities (Shah & Martinez, 2016). Indeed, citizen science projects have produced important scientific outcomes (see Bonney, Phillips, Ballard, & Enck, 2015 for review).

In addition to scientific goals, citizen science projects often strive to promote education in environmental science, commonly through curriculum-based projects for the K-12 student and teacher audience (Bonney et al., 2015). This is because schools are essential sites for environmental education (Alkaher & Gan, 2020; Cherif, 1992), and integrating formal curricula with citizen science initiatives provides a means to strengthen students' understanding of science and scientific inquiry skills through active participation in authentic research (Shah & Martinez, 2016). In fact, citizen science projects are becoming popular globally for improving science education (Bonney et al., 2009; Kelemen-Finan, Scheuch, & Winter, 2018; Paige, Hattam, & Daniels, 2015), in part because these contexts promote the social construction of knowledge – teachers and students participate as part of a community of practice to inquire into issues of societal importance (Gilbert, Bulte, & Pilot, 2011). In partnering with professional scientists, students formulate research questions, and collect, analyze, and communicate data about local or broader environmental issues (Houseal, Abd-El-Khalick, & Destefano, 2014; Trautmann, Shirk, Fee, & Krasny, 2012).

One environmental issue deserving explicit attention is climate change, and there has been increased interest in recent years towards addressing this issue in science education. This is critical because students show varying degrees of understanding about climate change and its underlying causes (Holmqvist Olander & Olander, 2017). To promote climate change education, studies emphasize making information about (global) climate change personally relevant and meaningful to students through local examples and contexts; fostering active participation and interactions with climate scientists; and supporting teachers with resources, such as lesson plans, to teach about climate change (Foss & Ko, 2019; Moncroe, Plate, Oxarart, Bowers, & Chaves, 2019). Yet realizing these characteristics in school is easier said than done. Citizen science approaches can address these needs.

4.1 Problem statement

To implement school-based citizen science, it is crucial to provide teachers and students with well-designed curricula. While student-teacher-scientist partnerships offer many benefits, such as high levels of student engagement (McLaughlin, Broo, MacFadden, & Moran, 2016), the partnerships are also challenging to implement. For example, scientists are concerned with the validity of scientific research involving student-gathered data, and teachers are concerned with time demands and aligning goals and activities with curriculum standards (Doubler, 1997). Hence, designers need to ensure that the quality of the fieldwork and data is maintained to attain important scientific benefits while also focusing on the learning goals to be attained (Shah & Martinez, 2016). Moreover, it is difficult to gather meaningful scientific findings over short time periods, but the lack of results risks lowering student interest (Barstow, 1997). Thus, whereas student-gathered data can contribute to long-term data sets, it is difficult for students to see clear patterns in the short-term.

The literature to date provides some resources for realizing school-based citizen science learning (e.g. Trautmann et al., 2012). However, curriculum designers still struggle, as they encounter many novel design challenges when integrating formal science curricula with citizen science. A core challenge is to design for fieldwork that is meaningful and engaging for students, feasible for teachers to implement, and rigorous enough for scientists to incorporate into their research. For example, how might designers equip students with sufficient understanding of curriculum-mandated concepts and practices to contribute valid and reliable data towards scientific research (Zoellick, Nelson, & Shauffler, 2012)? Further, how might students be trained to avoid bias in underreporting or overreporting data, which may have a bearing on the study’s intended scientific outcomes (Shah & Martinez, 2016)? And at the same time, how might designers balance opportunities for student ownership over fieldwork with adherence to the protocols and requirements of scientific research (Gray, Nicosia, & Jordan, 2012)?

The literature lacks precedents of designer thinking, which can provide insights into barriers, actions, and rationales underpinning the actual design work (Howard, Boling, Rowland, & Smith, 2012). What is also lacking is fine-grained information on considerations and processes that shape the evolving logic in designer thinking about how a proposed curriculum would support student learning. Designers rely strongly on their experiences and draw on known precedents of particular designs (Lawson, 2004), but direct experiences with a broad range of citizen science curriculum precedents are difficult to attain because integrating formal science curricula with citizen science is a relatively new approach. Specifically, the lack of knowledge about designer thinking poses difficulties in creating feasible and meaningful fieldwork experiences, in supporting students’ understanding of requisite scientific content, and in supporting teacher knowledge of scientific practices.

Therefore, this research article reports on a study that investigated how designers tackled challenges while developing a middle school citizen science curriculum on climate change. In so doing, the study also unpacks the considerations and processes that shape designer thinking in responding to emergent challenges. As described next, the study’s theoretical framework draws together three salient bodies of work: context-based learning, curriculum representations, and educational design processes.

4.2 Theoretical framework

4.2.1 Context-based learning

Context-based learning uses problem-based, student-centered practical activities to ensure that learning is meaningful and relevant to the contexts of real-world problems (Rose, 2012; Yu, Fan & Lin, 2015). Curricula centered on contexts that are relevant to students' lives can foster coherent understanding of scientific content (Bennett & Holman, 2002). Furthermore, the context-based approach has also been used to support science teacher learning in environmental education (Deveci & Karteri, 2020). When supporting context-based learning, experts recommend selecting contexts that exemplify key explanatory concepts and that are pertinent to students' lives and more broadly to societal concerns (Gilbert, 2006; Gilbert et al., 2011). For a citizen science ecology curriculum, a possible context is formed around investigating climate change phenomena, manifested in vegetation and bird responses. Gilbert and colleagues recommend attending to four main attributes of the context, (setting; background knowledge; behavioral environment; and specific scientific language). Elaborated below, these concepts feature prominently in the present study.

The first two attributes are considerations to which designers need to respond. The *setting* is a social situation within which students experience a specific context for the subject matter (Gilbert, 2006; Gilbert et al., 2011). The setting relates to a community of practice, such as one composed of scientists. For a citizen science curriculum on climate change, for example, the setting involves a community of scientists investigating climate-related phenomena in students' everyday environments and collecting longitudinal data on plants and animals. In engaging with this setting, students and teachers interact with one another and with scientists. The *background knowledge* attribute can be understood as the general knowledge that students need to participate productively in this setting, such as prior knowledge of statistical concepts for data collection and analyses (Gilbert, 2006; Gilbert et al., 2011).

Further, designers need to craft the following two attributes in the curriculum. The *behavioral environment* includes typical tasks in a science domain that address the context and exemplify fundamental scientific concepts (Finkelstein, 2005). Here it is important to think of activities that enable students and teachers to engage in authentic scientific inquiry. For a citizen science curriculum on climate change, possible activities relate to scientific practices including formulation of questions and hypotheses for fieldwork, and collection and analyses of climate-related data. The *specific language* attribute refers to discourse about specific scientific concepts and representations, including graphs and other visuals that are associated with the context (Gilbert, 2006; Gilbert et al., 2011). Designers should consider ways to help students participate in discourse about specific scientific concepts and practices (for examples of scientific ideas and practices, see science standards described in NGSS, 2013). For instance, citizen science curricula addressing climate change would include discourse about scientific concepts related to weather and climate.

In this study, the aforementioned attributes serve as an analytical lens to help the researchers understand designer thinking and processes underlying a citizen science curriculum. The attributes are used to interpret the decisions and activities of curriculum designers in supporting students' learning about climate change.

4.2.2 Designing multiple curriculum representations

Designer attention to context attributes is manifested through different curriculum representations. Building on classic representations of curriculum (Goodlad, 1979; van den Akker, 2003), this study focusses on three: intended outcomes, envisioned enactment, and written curriculum. Each representation contributes specific elements to the designers' theory of action, which helps them consider the logic behind how a curricular intervention will support student learning. A basic theory of action unpacks the relationships between inputs, processes, and outcomes (McKenney & Reeves, 2019).

For curriculum designers, it concerns how their designed inputs (i.e., the written curriculum), shape classroom enactment (i.e., the implemented learning and teaching activities), and ultimately engender certain results (i.e., especially student learning). They understand that this flow represents how schools experience curricula (see Figure 4.1, elements in dashed boxes). At the same time, when designers set to out create the curriculum, they consider multiple representations at once, and often map backward from articulating the intended outcomes, to formulating a vision for activity that will help attain those outcomes, to creating materials that will help bring the vision to life (see Figure 4.1, elements in solid boxes). Designers may proceed with an initial theory of action once potential ideas for the curriculum are in place, and the theory evolves as additional considerations emerge during the design process. Elaborated next, the present study investigates designer thinking and processes aimed at refining each representation for a citizen science curriculum, as well as aligning and recalibrating the overall theory of action to support student learning.

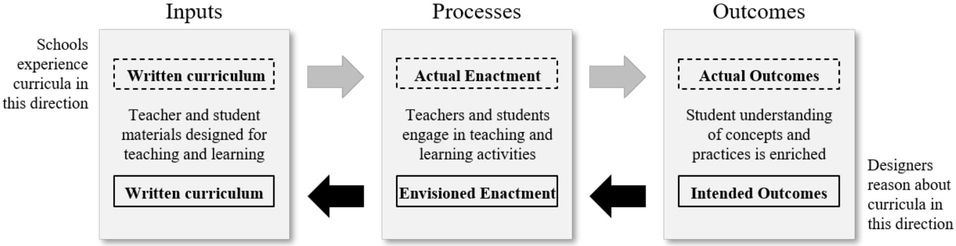


Figure 4.1: Designer theory of action.

For designers, the first representation created is often the *intended outcomes,* which are the student learning objectives to be attained (Thijs & van den Akker, 2009). In science curriculum design, these are generally the target scientific concepts and practices that students should comprehend. The intended outcomes may also specify how students should apply their understanding of the concepts and practices to perform specific tasks (Krajcik, McNeill, & Reiser, 2008). Common intended outcomes for citizen science include developing conceptual knowledge and skills of data collection and reporting (Phillips, Porticella, Constas, & Bonney, 2018). In view of the intended outcomes, designers can identify phenomena to make the target concepts and practices accessible to students (Krajcik et al., 2008), and can identify alternative student conceptions that would be important to address in the written curriculum (Rivet & Krajcik, 2004).

The second representation is the *envisioned enactment,* which involves instructional activities to help students and teachers attain the intended outcomes (Thijs & van den Akker, 2009). In science curriculum design, the designer vision may include student investigations with driving questions (Edelson & Reiser, 2006), a teacher role in facilitating discussions with students (Kolodner et al., 2003), and organizational matters involving student grouping and location of activities (Thijs & van den Akker, 2009). Examples of citizen science curricular activities include instruction on generating scientific questions, using particular tools for fieldwork, and analyzing and communicating findings in broad communities (Houseal et al., 2014). The design of instructional activities influences how deeply students engage with the target scientific concepts and practices (Tekkumru-Kisa, Stein, & Schunn, 2015).

This study also focuses on how designer ideals are manifested in the third representation, the *written curriculum,* typically taking the form of print-based and/or digital materials, such as teacher and student guide books (Thijs & van den Akker, 2003). The written curriculum incorporates designer considerations about the context attributes of setting and background knowledge, and contains supports to enact designer vision of the context attributes of behavioral environment and specific scientific language to attain the desired outcomes. In science curriculum design, materials to guide students' investigations contain prompts for planning experimental procedures (Kolodner et al., 2003), analyzing data (Songer, 2006), generating explanations grounded in evidence and scientific principles (McNeill, Lizotte, Krajcik, & Marx, 2006), and applying scientific knowledge to open-ended scenarios (Schwartz, 2006). Teacher materials present learning objectives and desired student responses, and offer suggestions for demonstrations and investigations (Schwartz, 2006). Additionally, tips are offered to lead class discussions (Pareja Roblin, Schunn, & McKenney, 2018), and educative elements explain students' typical conceptions (Roseman, Hermann-Abell, & Koppal, 2017), present science content to highlight during instruction (Davis, Palincsar, Arias, Bismack, Marulis, & Iwashyna, 2014), and provide strategies to enact scientific practices (Bismack, Arias, Davis, & Palincsar, 2015).

Examples of materials to enact citizen science are student journals containing questions to activate prior content knowledge (Harlin, Kloetzer, Patton, Leonhard, & Leysin American School high school students, 2018); worksheets containing stepwise instructions to support scientific practices (The Globe Program); lesson plans and teacher guides containing inquiry strategies, such as questioning to promote scientific thinking and critique (Trautmann et al., 2012), and fieldwork protocols (The Globe Program). The written curriculum is critical because scientific practices are challenging for students (Edelson & Reiser, 2006) as well as for teachers (Zangori, Forbes, & Biggers, 2013), and the extent of written support shapes students' understanding of the practices (McNeill et al., 2006; Songer, 2006).

4.2.3 *Educational design processes*

The above-mentioned curriculum representations come about and evolve through systematic, iterative processes comprising the core phases of analysis, development, and evaluation (McKenney & Reeves, 2019). The overall process typically begins with the *analysis* phase, which focuses on identifying and understanding the problem (McKenney & Reeves, 2019). In this phase, designers study the existing situation to help fine-tune their ambitions and approaches (McKenney & Reeves, 2019). Common activities include reviewing science curriculum frameworks to explore possible concepts and practices (Krajcik et al., 2008; Songer, 2006), and existing science curriculum materials to identify opportunities for student learning (Davis, Palincsar, Arias, Bismack, Marulis, & Iwashyna, 2014). Additionally, they gather data on the needs and context of the target teacher and student populations (Edelson, 2002), for example, through surveys conducted with school personnel (McKenney & Reeves, 2019). The resultant insights allow designers to conceptualize the challenge at hand and begin to envision the enactment of teaching and learning, pinpoint overall intended outcomes, and derive initial design requirements and specifications for the written curriculum (Edelson, 2002; McKenney & Reeves, 2019).

Then, the *development* phase focuses on conceptualizing and creating the curriculum (McKenney & Reeves, 2019). In this phase, designers generate fine-grained ideas for the intended outcomes, their vision for enactment, and the written curriculum. They map detailed specifications, and construct and revise prototype representations based on insights from both the preceding phase or (at later stages) following evaluation (McKenney & Reeves, 2019). Principal activities include reviews of prior research and curriculum frameworks to formulate specific learning goals and sequences of instructional activities (Krajcik et al., 2008; Songer, 2006). Designers draw on theory, inspiring examples, and local expertise (McKenney & Reeves, 2019). For example, they seek input from scientists on key scientific facts (Songer, 2006) and disciplinary practices (Edelson, Gordin, & Pea, 1999). They also prepare matrices to track how scientific concepts are treated in different contexts (Schwartz, 2006). This phase enables designers to define measurable intended outcomes (Gustafson & Branch, 2002), choose contexts and assemble relevant content (Pilot & Bulte, 2006), envision enactment of instructional activities, and prepare materials based on the design specifications (Gustafson & Branch, 2002).

Finally, the *evaluation* phase focuses on empirical testing of the curriculum (McKenney & Reeves, 2019). Designers test the curriculum formatively and summatively, acquiring data to plan subsequent revisions and to gauge the effectiveness of the intervention (Gustafson & Branch, 2002). Notable activities include gathering appraisal from external experts or advisory board members (Davis et al., 2014; Schwartz, 2006), pilots of initial prototypes, and classroom field tests of more mature versions of the curriculum (McKenney & Reeves, 2019). Designers observe teacher enactment (Davis et al., 2014; Roseman et al., 2017) and student engagement (Edelson et al., 1999); gather teacher feedback in person or via surveys about written materials, such as fieldwork protocols (Houseal et al., 2014); and assess student learning outcomes (Clarke & Dede, 2009). Results from this phase support empirical tuning of the intended outcomes, envisioned enactment, and the written curriculum.

4.2.4 Research goals, significance, and question

This study responds to calls for designing opportunities and materials to support student and teacher engagement with issues in environmental education, such as climate change (Foss & Ko, 2019; Monroe et al., 2019), and for producing rich cases tying designed products directly to designer process (Howard et al., 2012). Therefore, like process-oriented worked examples in other areas (Valero Haro, Noroozi, Biemans, & Mulder, 2019; van Gog, Paas, & Merriënboer, 2004), this study aimed to produce a detailed example of how designers make decisions in creating a school-based citizen science curriculum and how their decisions shape the evolving theory of action underlying the curricular intervention. The worked example contributes to curriculum design knowledge by elucidating designer rationales and processes for responding to key issues in designing school-based citizen science curricula. These descriptions, in turn, provide insights to other experienced and novice designers pursuing similar endeavors (Howard et al., 2012). With this aim, the study investigated the following question: *In designing school-based citizen science curriculum, how do designers shape the processes and decisions that contribute to their evolving theory of action over time?*

4.3 Methods

4.3.1 Case study approach

To address the research question, a qualitative interpretive case study (Merriam, 1988) was conducted of designer work involved in creating a single school-based citizen science curriculum. The method was suitable given that the target output was a detailed worked example of designer thinking and processes shaping a curriculum product (Howard et al., 2012). Specifically, the study sought to yield a case of designer thinking and processes to tackle the challenges arising in creating and integrating in-class curriculum with citizen science fieldwork. To that end, a participant-observation technique was followed to investigate phenomena that are otherwise difficult to capture in depth (Yin, 2014): the evolution of designer processes and solutions in response to emergent needs and challenges.

The curriculum was developed at an independent STEM educational research and development organization in the U.S., in collaboration with ecologists at a local scientific research institution. The project aimed to produce an in-classroom curriculum for middle school students (of ages 12-13 years), aligned with science education standards in the U.S. stressing students' understanding of core scientific concepts and practices. Students' learning was framed within a context of investigating climate change as it manifested in their local surroundings.

This curriculum design endeavor was in the service of a pre-existing partnership between the aforementioned ecologists and local schools, and it was intended to scale up to schools and science partners at a distance. The curriculum was crucial to help schools and scientists in the partnership to pursue both educational and scientific goals systematically. It aimed to support students and teachers to contribute data towards research conducted by partner scientists. Hence, the curriculum was aligned with a standardized fieldwork component that had been previously developed by the ecologists in partnership with local schools. For example, students measured leaf length and width, tree height, and canopy cover as observed near their school grounds. These data were intended to complement and contribute towards the ecologists' ongoing, long-term research on studying how ecosystem changes, including those in temperature and vegetation availability, influence the responses of migratory birds, such as the timing of their arrival. In so doing, the student-gathered data were expected to help develop a more complete understanding of how regional ecosystems influence bird behavior. In addition to the standardized fieldwork, there were opportunities for students to contribute data towards other broader citizen science repositories, such as the National Phenology Network's nature's notebook (USAPN).

The project also strove to promote students' understanding of key concepts and practices in climate science. The concepts included local bioindicators of global climate change, and the differences between weather, climate, and precipitation. The practices included generating hypotheses, analyzing longitudinal data sets, and using specific fieldwork techniques. The project reported significant improvement in students' understanding of specific topics, based on written pre- and post-assessments. For example, ~72% of the students distinguished satisfactorily between weather and climate on the post-assessment, as opposed to ~42% on the pre-assessment (Wilcoxon Signed Ranks Test, based on negative ranks: $Z= -5.253$, $p < .0001$). Similarly, ~79% of the students provided acceptably accurate or complete answers on the post-assessment in describing the impact of seasons on plant and animal life activities, compared to ~63% on the pre-assessment ($Z = -2.336$, $p = .02$). Finally, ~28% of the students provided accurate answers about possible species responses to climatic warming, in contrast to ~17% on the pre-assessment ($Z = -3.467$, $p = .001$).

4.3.2 Participants and research setting

A combination of purposeful and referral sampling was used to recruit designers of the curriculum project for this study. The project leader served as an informant to guide sampling choices (Yin, 2014) based on the designers' roles on the project. The project leader and an additional curriculum writer from the educational research organization were selected because they had contributed primarily to writing the curriculum materials. They had training in ecology and prior experience with school science curriculum development. The lead ecologist and an additional ecologist from the scientific research institution were selected because they had contributed primarily to the citizen science agenda and the fieldwork component. The ecologists also had prior experience in leading activities for environmental education. All participants signed informed consent documents prior to the start of the study. The researchers were not involved with the curriculum project prior to this research study, but they were granted access to relevant project documents, conversations with the participants, and an in-depth participant-observation research of the curriculum design process and resultant materials.[7]

4.3.3 Data sources

Multiple sources of evidence were used to triangulate data and produce credible and confirmable findings, as per recommendations in qualitative research (Guba, 1981; Yin, 2014). Data consisted of researcher-generated notes of the designers' weekly meetings and of one fieldwork enactment at a school site, and written feedback reports discussed with designers about their curriculum materials and design processes. The data set also included documentation produced by the designers (planning documents and memos; email communication; drafts of written curriculum; curriculum project grant proposal; teacher surveys; annual progress reports to the funding agency; and written pre-post assessments of student learning). Finally, there were five transcripts of designer interviews (two interviews with the project leader and an interview each with the remaining three participants).

4.3.4 Procedures

The first author served as participant-observer and was 'immersed' (Emerson, Fretz, & Shaw, 1995) in the team's routine design work. Her involvement began in the middle of the first year of the project, as the team was preparing for the first implementation. The data collection ended in the second year of the project, as the team continued preparing for the second implementation (see Figure 4.2). Following recommendations from the curriculum project leader, the researcher observed the designers' evolving theory of action behind the curriculum representations and shared her interpretations of the project's intended outcomes of students' learning, their vision for enactment, and the written curriculum as part of a team reflection activity. The overall procedure involved using various data sources in an overlapping manner to generate complementary and dependable findings (Guba, 1981).

As an *observer,* the researcher attended weekly team meetings and an enactment of the standardized fieldwork component at a school site. Casual direct observations (Yin, 2014) of the designers' processes and decisions in crafting and aligning the different curriculum representations were made over 17 months from January 2015 - May 2016. This prolonged engagement (Guba, 1981) allowed researchers to study the evolution of designers' work, culminating in three 'snapshots' (see Figure 4.2). Fieldnotes were generally written immediately after the observed events to capture complexities of designer work (see Emerson et al., 1995). The researcher also catalogued project documentation produced by the designers.

As a *participant,* the researcher shared with the designers two reports of interim analysis detailing their theory of action behind the curriculum representations, describing the associated design processes through which those representations were evolving , and noting possible next steps. The reports were based on interpretations arising from observational and document data, and they served 'to hold up a mirror' to help the design team reflect on their ongoing work

---

[7] This research was approved by the Institutional Review Board at TERC.

and identify critical issues to be addressed. Meetings were convened on two occasions with the design team to share the interim findings. Based on the study's theoretical framework, the 'mirror holding' meetings presented information about designer thinking behind the intended outcomes of student learning; the envisioned enactment of activities in the in-class curriculum and fieldwork to attain those outcomes; the written curriculum materials to achieve the vision and outcomes; and the design process followed to (re)shape these representations. In explicating the design process, the findings described the specific measures taken, requirements generated, insights gathered, and initial ideas proposed by the designers to support student learning.

These meetings also served as member checks (Guba, 1981) with designers to confirm and refine the reports as needed. The first report was discussed in May 2015, as schools were implementing materials for in-class and fieldwork activities. The second report was discussed in August 2015 as the team proceeded with initial redesign following the first implementation.

A short interview (Yin, 2014) of approximately 90 minutes was conducted with the project leader in June 2015 to better understand the design work that had occurred prior to gathering observational data, and to clarify other data emerging from observations and documentation. Whereas a set of questions about designer thinking and processes behind specific project materials guided the interview, a conversational tone was maintained to facilitate discussion of designer thinking. Sample questions were: *What were key design considerations in condensing the (original)*

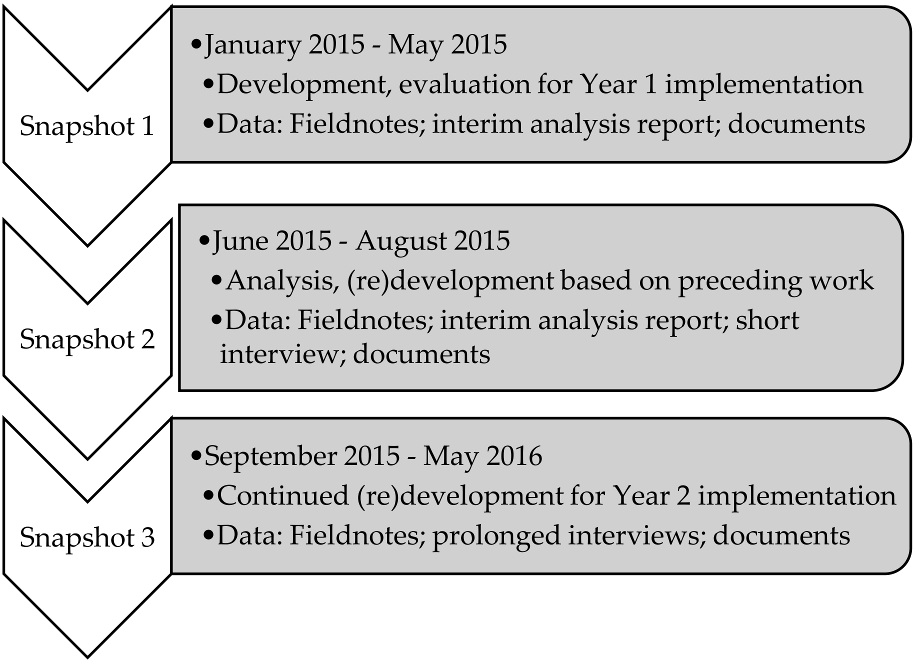


Figure 4.2: Snapshots, time periods, phases of the curriculum design work, and data sources.

3-week curriculum into a 1-week curriculum? What was the motivation for creating 'Species Briefs' materials, and how did you envision its use? What specific feedback did you get from teachers during the professional development workshop in fall of 2014?

Further, prolonged interviews (Yin, 2014) were conducted with designers in January 2016; each lasted approximately two hours and was carried out individually with the designers in a single sitting. The aim of the interviews was to inquire into designer rationales, processes, and insights shaping each curriculum representation and the overall theory of action. To facilitate the interviews, designers were provided with an updated version of the researchers' interpretation of their evolving theory of action, articulating the curriculum representations developed to date. This information was prepared based on emerging interpretations of observational and document data. The interviews also helped verify the designers' theory of action and revise it as needed.

Based on the theoretical framework of the study presented earlier, a semi-structured protocol was created to guide the interviews. A sample question about the intended outcomes of students' learning were: *Why were these goals for students' learning chosen by your team?* Designers were also asked about their vision for enactment, for example: *How did the team decide these [instructional] activities were important to support students' learning in this project?* Finally, a sample question about their design rationales and processes for the written curriculum was: *What sources of information guided your choices, for example, feedback from teachers, literature review, or observations made by the team?*

4.3.5 Data analysis

The analyses were conducted according to the three snapshots of the curriculum design work to uncover how designer processes and curriculum representations evolved in response to specific needs and challenges. The data were analyzed in two stages. First, during the 17-month period, fieldnotes of observations and document data were analyzed based on the theoretical framework and research question (Miles & Huberman, 1994) to examine designer processes and rationales behind the curriculum representations described previously. This step helped the researcher prepare interim analysis reports of the designers' evolving theory of action. The drafts were prepared by the first author and discussed with the co-authors until 100% consensus was achieved. The drafts were revised again after member checks with the designers. Additionally, the interview transcripts were analyzed by the first author to extract details about designer processes and rationales associated with specific curriculum representations. These interpretations were reviewed independently by the second author to confirm and extend the findings.

Second, following the 17-month period, the entire data set was reviewed to develop a comprehensive set of findings for a draft of a full case study report, with the multiple data sources serving to verify and elaborate the findings. This draft was discussed with the co-authors until 100% consensus was attained. Table 4.1 describes the coding scheme used to analyze designer work. Finally, the findings were clarified and corroborated through member check with the curriculum project leader (Yin, 2014).

Table 4.1: Coding scheme to analyze designer work.

Code	Explanation	Sample Quote
		Context-based Attributes
Setting	Social situation within which students engage in with a specific context for learning.	[Teacher Guide] The [scientific research institution] has been collecting data on bird biology and behavior for decades. The scientists have some ideas about how the change in temperature has created ecosystem changes that, in turn, have affected bird behavior, but they don't have time to look into all of those possibilities themselves. The [vegetation] data your students collect on their transects will complement the bird research that the scientists have been doing, and help create a more complete picture of what's happening to the regional ecosystems.
Background Knowledge	Relevant general knowledge needed for students to participate in the setting.	[Overview of lesson on the basics of weather and climate presented in the Teacher Guide] If you want to start with some more basic activities relating to taking temperature and the concept of "average temperature", see the [project's] long curriculum.
Behavioral Environment	Tasks exemplifying fundamental concepts and practices.	[Fieldwork protocol for leaf measures] Measure and record length to the nearest millimeter. Do not include the petiole/ leaf stalk. Measure and record width to the nearest millimeter. Width should be measured at the widest part of the leaf.
Specific Scientific Language	Student and teacher discourse about specific scientific concepts and representations.	[Teacher Guide] Discuss how changes in seasonal behavior could be used to tell us about changes in climate. How could we use bird data or other wildlife data as "bio-indicators" of what's happening to Earth's climate? Some points to revisit in this discussion: Signal vs Noise — what kind of data, and what amount of data might be enough to get a clear signal? For this, look at the graphs — it's pretty clear from them that any one or two years would be insufficient to get the clear picture provided by the 30-year dataset.
		Curriculum Representations
Intended Outcomes	The student learning objectives to be attained.	[Teacher Guide] Students should have a concrete understanding of how temperature affects evaporation rates and should be prepared to think about how the relationship between temperature and evaporation will affect wildlife as the planet warms.

Envisioned Enactment	Student learning experiences and teacher enactment envisaged to attain the outcomes.	[Designer notes from team meeting] We should have a bundle of activities around data analysis. What to look for, extracts from [ecologists' long-term] data, something about plant phenology and data - how do you look at a growing dataset? How do you represent the data? What does it look like if you are trying to analyze growing season?
Written Curriculum	Supports via print and/or digital materials for students and teachers.	[Questions in teacher material to enact data analysis activity] The cardinal [bird] data are about a change in range. In order to understand this, we need to think about questions like these: What limits a species' range? Why might a species' range change?
Design Processes		
Analysis	Designer work to plan overall goals and to derive initial design requirements and specifications.	[Designer notes from teacher implementation survey] [Teachers] wanted more orientation to the curriculum up front, several mentioned more about data analysis, and making clear the connection with the field work as well. One teacher noted the value to the students of taking data for more than a school assignment. For me it reinforces the urgency of giving them some other data to collect that they can link to regional or national studies or citizen science activities.
Development	Designer work to identify target content, instructional activities and sequences, and to produce written curriculum.	[Designer interview] In initial conversations about species to choose [for students' data collection], [ecologist] was saying, well, we'll go to each site, and we'll think about, what are the common species there, and those are the ones [students will] collect. On the other hand, it was really important for there to be student choice. And so [region] Phenology Network framework felt like the right structure to impose certain kinds of rigor and clarity, and yet allow freedom. I consulted with [the ecologists] about species, but also had some in my pocket from this other experience that were like the obvious ones for [region], and having looked around the national phenology calendar database.
Evaluation	Designer work to test and inform prototype revisions.	[Designer observations of student-gathered data] Some students converted their English units to metric, while others did not. Others may have measured circumference instead of diameter and failed to divide by Pi. A few students measured the thickness of each leaf instead of the width. Many students failed to fill in metadata at the top of the data sheets.

4.4 Results

The data analysis revealed three intended outcomes of students' learning, which are used to organize the results section: students' understanding of key scientific practices; of climate science concepts; and of the value of local citizen science action. Each sub-section begins with a paragraph describing the intended outcome and relevant designer work that occurred prior to gathering participant-observational data for this study, followed by work observed as part of the research study (Snapshots 1, 2 and 3). Each sub-section also includes a figure depicting how the four attributes of context-based learning (setting, background knowledge, behavioral environment, specific scientific language) manifest in specific designer tasks related to each outcome. Thereafter, each sub-section presents findings synthesized from multiple data sources (as indicated in Tables 4.2, 4.3, and 4.4) that describe how designers shaped their processes and decisions to contribute to their evolving theory of action over time. Each snapshot reports envisioned enactment and/or written curriculum for the intended outcome and designer processes and rationales behind those representations.

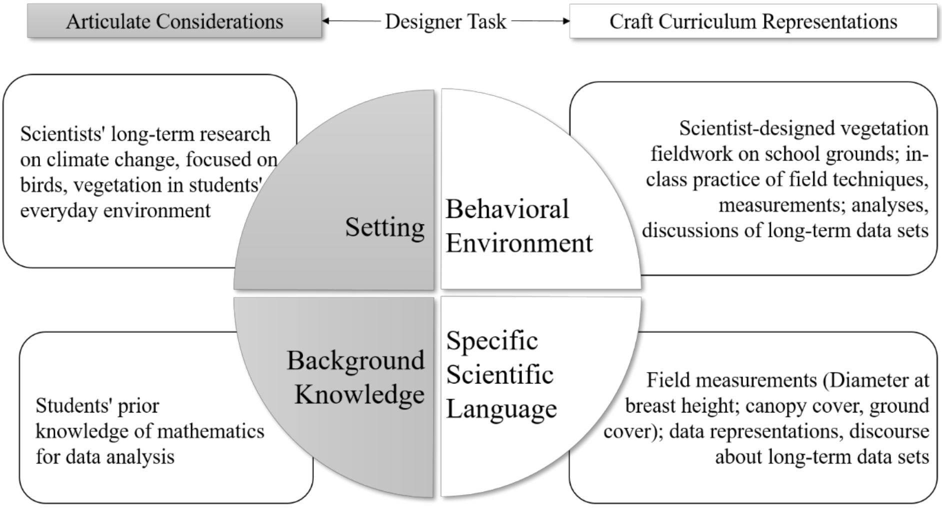


Figure 4.3: Manifestations of context attributes for scientific practices.

4.4.1 *Intended outcome 1: Scientific practices*

Designers aimed for students to understand scientific practices, such as using specific field techniques for measurement, generating hypotheses, analyzing data and distinguishing signal from noise in longitudinal data sets. The target practices were related to the scientist-designed, standardized vegetation fieldwork component with which the in-class curriculum was meant to align (see Figure 4.3). In fall of 2014, external advisers had recommended tightly aligning the standardized field work with the in-class curriculum. Therefore, designers emphasized signal vs. noise detection in long-term data sets to help students understand how collecting long-term data could yield clear trends that would not be evident in short-term data.

During this time, teachers expressed interest in integrating science with mathematics via data analysis activities, and stressed simple descriptive statistics, data quality, and data sets.

4.4.1.1 Snapshot 1

Student, teacher, and scientist interactions all take place within the *setting* of the latter's long-term research on bird movements and climate change. Designers imagined scientists would personally assist teachers and students to collect specific long-term standardized vegetation data on leaf length and width (to study leaf-out), canopy cover, and tree height and diameter at breast height (DBH).

As part of the *behavioral environment*, in-class curriculum activities were aligned with the scientists' research questions. To sharpen this alignment, following expert appraisal, the in-class curriculum was shortened from a 3-week to a 1-week sequence of lessons situating the fieldwork within foundational climate science theory, and it was organized around the central theme of signal vs. noise. The student materials and teacher guide included stepwise instructions to practice field measurements and techniques prior to fieldwork. The written curriculum also contained protocols and record sheets with procedures and kits (containing micrometers and DBH measuring tape) to enact the standardized fieldwork.

With respect to *specific scientific language*, the ecologists emphasized certain vegetation measurements and techniques because of the connection between vegetation and birds (vegetation as indirect indicator of insect availability) and because vegetation measurements were easier to implement with schools than bird measurements. The main considerations of the designers were to incorporate easily implementable techniques (e.g., using measuring tape to record leaf length and width); accessible and relevant measurements related to easily identifiable and abundant vegetation; reasonable sample size of vegetation data; and potential to generate clear meanings and long-term results from the fieldwork.

4.4.1.2 Snapshot 2

The designers' envisioned enactment shifted as they considered providing additional material supports for conducting standardized fieldwork, while reducing in-person assistance from scientists. This shift was critical to their overall endeavor of designing a scalable school-scientist partnership model. Further, their vision of the *behavioral environment* expanded to include supplementary in-class activities for analyses of authentic data sets, for which designers considered both the standardized vegetation data and other existing long-term data sets. As an ecologist elaborated, they wanted students to "have at least some sort of exposure to field techniques to demystify science," to make science "more accessible", and to help students realize that "anyone can contribute to this database."

This vision was influenced by designers' evaluation work. Previously in spring of 2015, they had observed the standardized fieldwork, noting the extent of teacher preparation, student engagement and understanding, and logistical challenges in data collection. Teachers and students were found to have insufficient understanding of fieldwork techniques. Teacher survey results confirmed the educational value of the fieldwork, while revealing that teachers needed more support to enact field techniques and data analysis activities. There were also difficulties with taking particular measurements, such as DBH and tree height. In a document describing observations of student-gathered data, an ecologist noted that the process was "less-than-precise and open to enormous amounts of individual variation." Additionally, the ecologists noted lack of metadata, failure to convert units of measurement, and incorrect measurements and calculations in student-gathered vegetation data.

To develop the written curriculum, designers began planning supplementary data analysis activities. Key considerations were students' prior knowledge of mathematics and state standards for mathematics content in target grades. Designers also emphasized data sets that were concrete, presented some variability, and had the potential to show obvious patterns, thus yielding clear answers and making data analyses rewarding to students. During team meetings, designers reasoned that to motivate teachers to enact data analytic activities, the measurements needed to show changes directly related to climate change, for example, leaf growth as opposed to tree height. Furthermore, to help students and teachers see how the data analytic activities fit with the curriculum and fieldwork, it was important to show conceptual links to foundational climate science theory. During interviews, a curriculum writer explained that "integrating math into science, especially anything that has to do with environmental science, is a real challenge. One of the typical issues is that you get teachers to collect data and they don't want to do the analysis." Providing teachers with access to authentic, longitudinal data sets was considered as a key benefit of partnering with scientists. However, as the curriculum writer clarified, "scientific data sets are incomprehensible outside of the research project most of the time. So, there has to be an intermediary process."

To that end, the ecologists proposed ideas for analyzing longitudinal bird data from their own research and vegetation data from the standardized fieldwork. They visited school grounds to gather vegetation data to compare to student-gathered data and to select a subset of the data for inclusion in the curriculum.

4.4.1.3 Snapshot 3

To develop teacher guides for in-class data analysis activities as part of the *behavioral environment*, the ecologists identified suitable variables from their data sets. Guided by considerations about *background knowledge*, the curriculum writers selected a small set of variables from those and structured the complex data sets to suit target students' data analytic skills and mathematics learning standards. They included background information on relevant species and key concepts, research hypotheses, stepwise procedures, and questions to prepare, analyze, interpret, and discuss long-term data sets. The written curriculum thus reinforced *specific language* via data representations and supports for scientific discourse. These supports were crucial because scientific data pose challenges in sense-making for non-scientists. Therefore, the data sets needed to be problematized and simplified to foreground key ideas.

Based on errors and limitations in student-gathered vegetation data from the standardized fieldwork, the ecologists revised fieldwork protocols to embed links to video tutorials illustrating specific techniques (e.g., using measuring devices to record leaf length and width to the nearest millimeter). Additionally, they revised data sheets to reinforce accurate data collection (e.g., leaf length/width data sheets now included details like plant species, latitude and longitude). Based on a survey to assess teacher access to different technologies, the ecologists also prepared a written tutorial for using basic GPS-based devices to aid standardized fieldwork.

Table 4.2 summarizes key findings about scientific practices and indicates the data sources from which those findings were synthesized.

Table 4.2: Data sources of key findings about scientific practices.

Designer work	**Key findings**	**Designer Interviews**	**Designer Team Meetings**	**Design Documents**[8]
Envisioned Enactment	Standardized vegetation fieldwork (snapshot 1)	x	x	x
	In-class supplementary data analyses, discussions (snapshot 2)	x	x	x
Written Curriculum	Protocols, data record sheets, written and video tutorials for standardized fieldwork (snapshots 1, 3).	x	x	x
	Background information, stepwise procedures, questions for data analyses (snapshot 3)			x
Designer Considerations and Processes	Easy techniques, accessible measurements, reasonable sample size for standardized fieldwork (snapshot 1)	x		
	Concrete measurements having variability, clear links to climate change and theory for data analysis (snapshot 2)		x	x
	Observations of fieldwork, student-gathered data, teacher surveys revealed fieldwork challenges (snapshot 2)	x	x	x
	Students' prior knowledge, state mathematics standards considered for data analyses (snapshot 2)	x	x	x
	Input gathered from teacher survey on available technology for fieldwork (snapshot 3)		x	x
	Vegetation and bird data gathered from ecologists for data analytic activities (snapshot 3)	x	x	x

---

[8] The design documents for this intended outcome consisted of drafts of the written curriculum, designer emails, memos, planning documents, curriculum project grant proposal, and teacher surveys.

4.4.2 *Intended outcome 2: Conceptual understanding*

Designers stressed student comprehension of key climate science concepts, such as weather and temperature. They also emphasized understanding the impact of climate change and the links between local and global climate change (see Figure 4.4). In Fall 2014, teachers had expressed the need for grade-appropriate readings to integrate science and literacy. They stressed shortening the 3-week curriculum because it spanned content across grade levels. Furthermore, external advisers recommended deeper treatment of key scientific concepts, improved teacher access to content, and a condensed curriculum to address constraints on teachers' time.

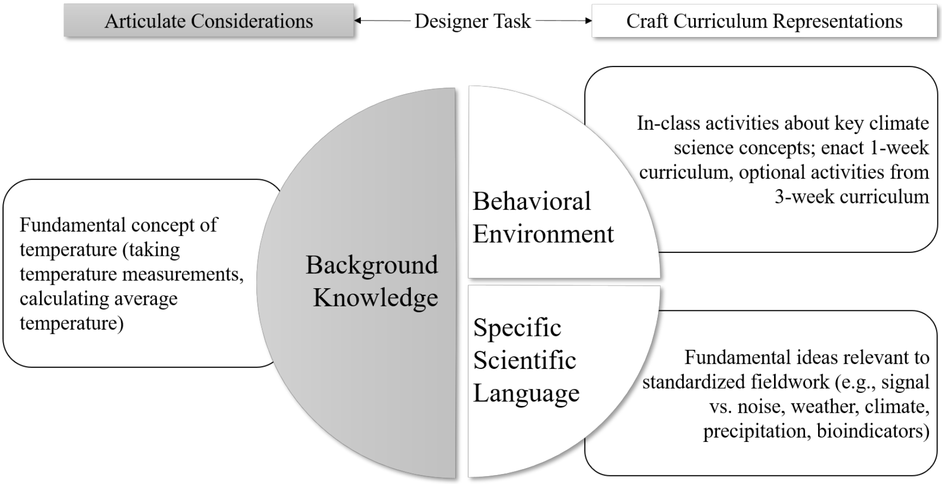


Figure 4.4: Manifestations of context attributes for conceptual understanding.

4.4.2.1 Snapshot 1

For the *behavioral environment*, designers envisioned a range of in-class activities to introduce *specific language* related to key climate science concepts for motivating the standardized fieldwork. As explained during interviews, their vision included providing non-fiction science readings for background content to guide optional student inquiry into particular species.

Following expert appraisal, the written curriculum was condensed to a 1-week version highlighting specific organismal responses of local species and some global examples. For the *behavioral environment*, the student materials provided context for lessons and stepwise questions and prompts. The teacher guide clarified target concepts and connections to activities and lessons, and it also contained: stepwise prompts, questions and intended student responses, definitions of key terms (i.e., climate vs weather), and provided optional questions for lesson review, extension activities, and background readings. Finally, short non-fiction science reading resources called 'Species Briefs' were provided separately to enrich student learning. The readings described the 'range' of habitats of local organisms, life histories and responses to climate change.

To develop the 1-week curriculum, the curriculum writers attended to the *specific scientific language*, focusing on concepts that were not addressed in other subject areas, were typically challenging to enact, were related to longitudinal data collection, and were essential to contextualize the standardized fieldwork. Examples of local phenomena and species were included to motivate student learning about climate science as it related to their everyday lives. During an interview, as a curriculum writer explained their choices for the 1-week curricular content,

> *The conceptual framework behind the science was more important. But math, the geographical aspects, those are skills that one can learn in other contexts and then apply. But learning the concepts of signal vs. noise, the history of climate science, and what goes into figuring out how to do research, and how to get meaning from the data, that stuff is more important, both in terms of training scientists and in terms of training non-scientists who can come to terms with science in their everyday lives.*

To create 'Species Briefs', the curriculum writers drew on species descriptions and a framework of organismal responses developed in a prior project, using species whose climate responses had been reported in the scientific literature. They also considered target students' reading level to identify accessible content.

4.4.2.2 Snapshot 2

The envisioned enactment of the *behavioral environment* evolved to emphasize teaching the 1-week curriculum because it was foundational for the standardized fieldwork. Designers also imagined including topics from the 3-week curriculum as optional modules based on students' background knowledge. This vision was shaped by the evaluation phase. Designers had observed that the 1-week curriculum had not been taught prior to the standardized fieldwork, and as an ecologist noted, consequently, students and teachers had 'little idea as to why [they] were in the field.' A teacher survey indicated spotty enactment of the 1-week curriculum due to time constraints and adaptations based on students' background knowledge. Teachers also expressed interest in enacting some activities from the 3-week curriculum. The written curriculum, however, was not immediately redesigned.

4.4.2.3 Snapshot 3

The vision for in-class activities of the *behavioral environment* continued to be refined. Designers imagined teachers would help students develop firm understandings of key concepts via observations and evidence, and guide students to conduct research on life histories of specific organisms. They also considered adapting the 1-week curriculum according to students' learning needs and class time constraints.

These refinements emerged from the evaluation phase. First, the curriculum writers analyzed written pre-post assessments of student learning, noting the accuracy, completeness, relevance, and specificity in student responses. In so doing, they identified concepts, such as temperature and precipitation, that were difficult for students. Second, during a meeting with external advisers, it was recommended that the written materials specify the understanding goals of the science content for teachers. In response, the teacher guide for the 1-week curriculum included understanding goals of lesson activities, and pointers to activities from the 3-week curriculum on taking temperature and calculating average temperature to adapt to students' *background knowledge.*

The written curriculum also included educative notes for teachers. The notes reinforced *specific scientific language*, explaining students' emergent or alternative understanding of challenging ecological concepts, such as distinctions between weather and climate, exemplified these with student responses from pre-post assessments, and offered strategies to address students' thinking. The curriculum writers honed the educative notes following feedback from the ecologists about including specific species examples and case studies to support in-class activities.

Table 4.3 summarizes key findings about conceptual understanding and indicates the data sources from which those findings were synthesized.

Table 4.3: Data sources of key findings about conceptual understanding.

Designer work	**Key findings**	**Designer Interviews**	**Designer Team Meetings**	**Design Documents**[9]
Envisioned Enactment	Guide optional student inquiry (snapshot 1)	x		
	Teach 1-week unit as foundation before standardized fieldwork (snapshot 2)	x	x	
	Teach optional 3-week unit as appropriate to student needs, interests (snapshot 2)		x	
Written Curriculum	Lesson context, stepwise questions, prompts in student materials (snapshot 1)			x
	Definitions, understanding goals, intended student responses, stepwise questions in teacher materials (snapshot 1, 3)		x	x
	Educative teacher notes to explain, exemplify, address student thinking (snapshot 3)			x
	Optional short species briefs (snapshot 1)	x		x
	Selected content essential to situate fieldwork (snapshot 1)	x		

---

[9] The design documents for this intended outcome consisted of drafts of the written curriculum, designer emails, memos, planning documents, annual progress reports to funding agency, teacher surveys, and written pre-post assessments of student learning.

Designer Considerations and Processes	Included local examples to motivate students (snapshot 1)	x		
	Surveyed species frameworks from prior project (snapshot 1)	x		x
	Observations revealed in-class unit not taught prior to fieldwork (snapshot 2)	x	x	x
	Teacher survey revealed need for in-class unit adaptation (snapshot 2)			x
	Pre-post written assessments revealed student difficulties with specific concepts (snapshot 3)	x		x

4.4.3 *Intended outcome 3: Valuing local action*

Designers aspired for students to understand how local citizen science endeavors can contribute to broader scientific research on climate change (see Figure 4.5). In fall of 2014, external advisers had noted that the 3-week curriculum did not sufficiently motivate students for scientist-designed standardized fieldwork. They recommended explicating connections to the long-term research and fieldwork goals of the ecologists.

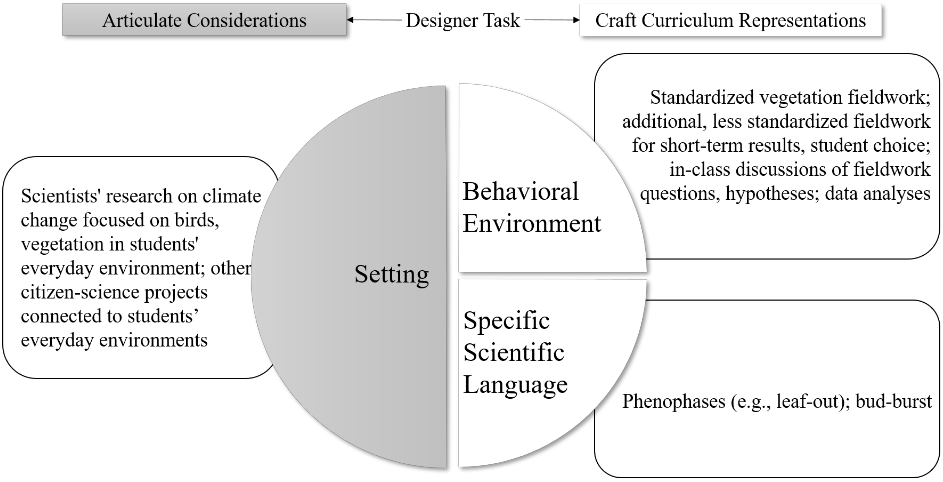


Figure 4.5: Manifestations of context attributes for valuing local action.

4.4.3.1 Snapshot 1

Following the appraisal from external advisers, designers envisioned connecting students' standardized vegetation fieldwork to the ecologists' long-term research on bird responses to climate change, as evidenced in the local surroundings. To do so, with respect to the *behavioral environment*, they imagined whole-class discussions about questions and hypotheses behind the research. With input from the ecologists, the curriculum writers included in the 1-week curriculum the rationale and hypotheses of the fieldwork to explain how it contributed to the scientists' current research on birds, i.e., *the setting*. This information aimed to help both teachers and students understand how the in-class activities and fieldwork were in the service of the scientists' research program. Whereas vegetation measurements may have low appeal for secondary school students, designers hoped that the ultimate connection to local bird research would motivate students. As a curriculum writer recalled during the interviews,

> *The [standardized] data collection that the students are doing is actually related to [the scientific research institution's] hypotheses and research questions. And it took me a while to realize that it was actually really important to foreground those. And I have a little confirmation of this, because when I handed [the curriculum material about articulating the research program] to [partner teachers], they were really grateful because it was a missing ingredient. And then their response was, the thing that gets these [students] really excited is we're really doing this for real scientists.*

4.4.3.2 Snapshot 2

The vision to connect students' fieldwork with the *setting* of ongoing scientific research expanded as designers considered additional, supplementary citizen science activities. These activities were crucial to promote student ownership over data collection, yield short-term results with clearer contributions to authentic, growing data sets, and thereby provide more rewarding experiences with data. Designers envisaged students would formulate research questions, gather data, compare data sets from other participating schools, and contribute local data to broad citizen science movements.

This expanded vision stemmed from designers' evaluation work. A prospective teacher participant stressed greater student choice in fieldwork activities. Moreover, designers wrestled with the standardized, long-term vegetation data because some measurements, such as tree height did not yield 'immediate' results in terms of climate change, and they did not present enough variability to help students learn about the natural world. Limitations and errors in student-gathered vegetation data noted previously also influenced designers' decision to emphasize additional channels for collecting less standardized data, thus improving the chances of contributing the data to scientific research endeavors. Finally, during team meetings, designers reasoned that connecting students' fieldwork clearly with specific scientific research programs would augment its authenticity.

Therefore, the curriculum contained a teacher guide for an optional 'Phenology Calendar' activity. For *specific scientific language*, the teacher guide provided background information and briefs on phenology observations. It presented the rationale behind collecting phenology data, criteria for collecting data on phenophases from different taxa – birds, plants, insects - and guidelines for reporting findings. With respect to the *behavioral environment*, there were guidelines for in-class data analyses and extension activities.

To develop these materials, the team drew inspiration from existing citizen science phenology programs. The curriculum writers referred to a regional phenology network framework to select useful indicator species, derive phenological indicators to observe, and suggest a structure for the activity. In addition to providing student choice, they emphasized data common to all participating schools to help students learn from variability in school sites. Accordingly, after surveying vegetation and birds near the school sites, the ecologists selected species and indicators that were easily accessible and recognizable to students, had easily observable phenophases, and were practical to measure, such as first frog calls, leaf-out, and flowering. They stressed presence/absence measures, rather than those requiring precise measures of quantity. See the following interview quote from an ecologist about the considerations behind choosing species and indicators:

> *We had to choose birds that are really obvious. Can you see a robin coming back after spring migration? Can you find red-winged blackbirds? These are birds that anyone can recognize. Three of the schools we are dealing with now have ospreys very close by in the areas where they are measuring plants. So the students and teachers can be familiar with ospreys. We had to choose simple birds, simple plants, simple indicators. Is there a yellow dandelion flower? Probably the first time a student sees a dandelion, it might be in their backyard. But that's okay. What [students] are doing is, they are learning the technique of, when do things first emerge, and putting it into the context of, is this happening earlier? Is it due to climate change? We had to really adapt the species to the school year, the curriculum, the [seasonal] timing that we had, and what was practical in terms of getting students measuring.*

4.4.3.3 Snapshot 3

With respect to the *setting*, designers continued to ponder citizen science opportunities to help students contribute data to scientific research projects with a clearly articulated research agenda. This additional fieldwork was critical to make climate science more accessible to students and to develop their awareness of how non-scientists can contribute to it. The refined vision emerged from designers' development work. They noted challenges in using student-gathered standardized vegetation data for immediate scientific research on climate change. Whereas the standardized data collection 'demystified science', it was important to include measurements whose relevance to climate change was understandable to students.

The written curriculum now included supports for fieldwork in the service of a scientific research project on twigs cut from dormant woody plants. The project was being conducted at a local university to understand plant responses to climate change. For *specific language*, there were educative notes on science background information, significance of the scientific research project, and science briefs on relevant topics, such as leaf-out and bud-burst. To clarify and connect the fieldwork to the *setting* of the scientists' research, there were research questions and stepwise procedures for data identification, collection, monitoring and contribution. For the *behavioral environment*, the materials also supported in-class data analysis and comparisons across sites. The curriculum writers gathered input from scientists at the university to prepare these materials.

Towards the end of this period, to reinforce an array of learning activities and connections therein, curriculum writers also began highlighting a 'package' metaphor consisting of a collection of in-class and fieldwork activities. To manifest this metaphor in the written curriculum, a menu of options was created. The menu presented packages of scientific research question, data collection techniques (including the standardized vegetation data), and related in-class curriculum activities. It offered tips for field activities and protocols contributing to different scientific research programs on climate change. Finally, it identified key science concepts behind each activity and relevant science and mathematics learning standards and in-class activities. The menu was developed after the researchers had finished collecting data for the present case study. Hence, the paper does not report the design process behind this material.

Table 4.4 summarizes the key findings about valuing local action and indicates the data sources from which those were synthesized.

Table 4.4: Data sources of key findings about valuing local action.

Designer work	**Key findings**	**Designer Interviews**	**Designer Team Meetings**	**Design Documents**[10]
Envisioned Enactment	Class discussions to connect standardized fieldwork to scientists' long-term research (snapshot 1)			x
	Optional data collection to promote student choice, short-term results, contribution to authentic research (snapshots 2, 3)	x	x	
Written Curriculum	Standardized fieldwork rationale, hypotheses clarified in 1-week curriculum (snapshot 1)	x		x
	Briefs, data collection criteria, stepwise guidelines for analysis, reporting in teacher guide for phenology calendar activity (snapshot 2)			x
	Educative notes on science briefs, research significance, stepwise procedures for data collection, analysis, contribution for university project (snapshot 3)			x

---

[10] The design documents for this intended outcome consisted of drafts of the written curriculum, and designer emails, memos, and planning documents.

	Tips, protocols for 'packages' of fieldwork, in-class activities (snapshot 3)			x
Designer Considerations and Processes	External appraisal stressed stronger motivation for standardized fieldwork (snapshot 1)	x	x	x
	Teacher feedback stressed greater student choice in fieldwork (snapshot 2)		x	
	Limitations in student-gathered data implied need for less standardized data (snapshot 2)		x	
	Citizen science examples, regional phenology network surveyed for indicators (snapshot 2)	x	x	
	Vegetation, birds near school sites surveyed to identify potential species for phenology calendar activity (snapshot 2)	x	x	
	Focus on easily recognizable, observable, measurable species, indicators for phenology calendar activity (snapshot 2)	x	x	

4.5 Discussion

This participant-observation case study sought to generate a detailed worked example of designer thinking and processes in tackling emergent challenges while creating a school-based citizen science curriculum. To do so, the study answered the following question: *In designing school-based citizen science curriculum, how do designers shape the processes and decisions that contribute to their evolving theory of action over time?* The main findings are summarized in Tables 4.2, 4.3, and 4.4, and the key insights from these findings are elaborated below.

4.5.1 Reflections and implications for educational design

A holistic reflection on the findings reveals four key considerations of designers that contributed to their evolving theory of action for supporting school-based citizen science. This section describes each consideration in light of existing literature and presents implications to aid those designers wishing to pursue similar endeavors.

4.5.1.1 Creating the learning environment around the fieldwork

The initial model of citizen science embodied in this curriculum was of the contributory type (Bonney et al., 2009), involving scientist-designed research goals and protocols based on their prior work. Designers wanted students to primarily collect and contribute specific long-term, standardized vegetation data towards the research goals of the ecologists in studying migratory bird responses to climate change. But the connection between local vegetation data and bird data was initially not clear to teachers or students, nor was the rationale of collecting long-term data in studying climatic phenomena. Hence, designers revised the in-class curriculum to situate fieldwork within foundational climate science theory and aligned in-class activities with the scientists' research goals. Making these points explicit is crucial for students' engagement with the context of the curriculum, and to help them appreciate how the science they learn is relevant to their lives and to society more broadly (see Gilbert, 2007).

Another crucial need was to support students in analyzing data sets. Here too, designers considered sense-making difficulties in engaging with authentic scientific data sets. By providing structures and stepwise guidelines in the written curriculum, the designers strove to make this scientific practice less complex while highlighting its core elements (Edelson & Reiser, 2006). Data analysis is an important scientific practice emphasized in curriculum frameworks (NGSS, 2013). Therefore, to help students and teachers engage with this practice, as instantiated in the present case, designers may select and curate data sets gathered from scientific research. To do so, they may administer surveys to inquire into teachers' needs for meeting curriculum standards (Doubler, 1997; Edelson, 2002) and draw on partner scientists' expertise (McKenney & Reeves, 2019.

4.5.1.2 Tackling concerns about data quality and utility

The designers of this curriculum noted limitations in student-gathered standardized data and insufficient teacher preparation to facilitate fieldwork. These issues made it difficult to use student-gathered data in contributing towards actual scientific research, which is a key goal of citizen science endeavors. Indeed, the concerns with data quality and utility are common in implementing citizen science projects (Houseal et al., 2014; Jordan, Ehrenfeld, Gray, Brooks, Howe, & Hmelo-Silver, 2012). To respond to this problem, designers refined the instructional activities. Specifically, designers supplemented the fieldwork protocols with video and written tutorials and revised the data sheets to clarify fieldwork techniques and reinforce accurate data collection. Therefore, to help students contribute rigorous data towards scientific research, as exemplified in this work, designers may attend carefully during formative evaluation of the curriculum implementation (Gustafson & Branch, 2002), observing teacher facilitation, student engagement, and the quality of student-gathered data.

4.5.1.3 Making scientist-designed fieldwork engaging to students

Because the standardized vegetation fieldwork was initially not strongly motivated for students in this curriculum, designers modified the behavioral environment in two ways. First, they clarified in the 1-week curriculum the fieldwork's purposes and contributions to the long-term research on birds being conducted by the ecologists. The written materials supported in-class discussions about underlying questions and hypotheses. Second, designers refined their vision to emphasize teaching the 1-week curriculum prior to the fieldwork. These measures thus aimed to help students value and engage productively with the setting (related to a community of scientists), in which they were to investigate climate change and learn the underlying science (Gilbert et al., 2011). In fact, communicating clearly a scientific agenda and potential utility of the data is a chief consideration in designing citizen science projects (Bonney & Dickinson, 2012). To do so, as seen in this case study, designers may seek feedback from external advisers (Schwartz, 2006).

4.5.1.4 Balancing scientific and educational goals

A pressing concern with scientist-designed fieldwork is that students have little ownership over the underlying scientific agenda; they have few opportunities to engage with key scientific practices that go beyond data collection. To resolve this issue, the designers of the present curriculum developed materials to support additional student investigations. These revisions provided greater fieldwork options, including more structured inquiry embodied in the standardized vegetation fieldwork and more open inquiry embodied in the 'Phenology Calendar' activity (Trautmann et al., 2012). They enabled greater student choice in formulating research questions and hypotheses, identifying suitable measurements, collecting and analyzing data, and communicating the findings. These design decisions are consistent with prior work that emphasizes student experience of the full scientific inquiry process to help them develop deep understanding of scientific concepts and practices (Doubler, 1997). Studies have argued for helping students plan and conduct their own investigations related to authentic scientific research (Houseal et al., 2014; Trautmann et al., 2012). Hence, to support varied fieldwork opportunities, as demonstrated in this case, designers may draw on teacher feedback, their own observations of the fieldwork implementation, local expertise, and inspiring examples of other citizen science programs and related networks (McKenney & Reeves, 2019).

4.5.2 Study limitations and implications for educational research

Whereas the participant-observation approach presented several affordances, there were also some limitations. These are elaborated below, along with methodological and theoretical implications.

First, the present findings have limited generalizability, as with all case studies. Therefore, further research needs to be conducted to develop a broader knowledge base of designer thinking and strategies for integrating formal curriculum with citizen science fieldwork. Second, the study reported in this paper concluded before the designers conducted the final evaluation and redesign of the curriculum. As a result, these phases of the design work were absent in the present research. This also meant that information on the attainment of specific educational and scientific outcomes was not available during the study. Hence, the data analysis could not uncover the effectiveness of the designers' processes and decisions with respect to the different curriculum representations. Therefore, future studies could include such data to unpack how specific designer decisions influence student motivation and attitudes, teaching practices, and the utility of student-gathered data for scientific research.

Finally, the present analyses did not unpack the underlying partnership model involving students, teachers, and ecologists, and the role of the curriculum writers in 'mediating' this partnership. Specifically, future research could uncover how scientists and school partners can be supported to learn from one another, as they cross boundaries between the cultures of schools and scientific research. Prior work highlights various mechanisms by which learning occurs at the boundary, such as those of identification and reflection in which individuals come to understand the differences among institutional practices (Akkerman & Bakker, 2011). How might designers create specific supports that embody these and other mechanisms? This is a fruitful direction for future work as scientist-educator partnerships gain prominence to support science education (Drayton & Falk, 2006).

4.5.3 Final remarks

This study uncovered the challenges encountered by designers of school-based citizen science curricula aimed at supporting environmental education. The study also portrayed their responses to those challenges, which can be useful to others engaged in similar endeavors. As a modest but unique contribution in this direction, the present study reveals not only the different ways in which designers' ideas were represented in the curriculum, but also brings to the fore the meticulous thinking and measures behind the evolution of those ideas. Through its detailed description of designer considerations and processes that helped refine their theory of action, the study thus enables a vicarious experience of the present design that can help other designers derive insights to guide their own choices (Howard et al., 2012). Finally, the four considerations as noted from the designers' initial work highlight key issues to attend to in other projects involving school-based citizen science for environmental education.

References

Akkerman, S. F., & Bakker, A. (2011). Boundary crossing and boundary objects. *Review of Educational Research, 81*(2), 132 – 169.

Alkaher, I., & Gan, D. (2020). The role of school partnerships in promoting education for sustainability and social capital. *The Journal of Environmental Education*, 1-18.

Barstow, D. (1997). The richness of two cultures. In *National Conference on Student & Scientist Partnerships* (pp. 33 – 37). Cambridge, MA: TERC and Concord Consortium.

Bennett, J., & Holman, J. (2002). Context-based approaches to the teaching of chemistry: What are they and what are their effects? In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), Chemical education: Towards research-based practice (pp. 165-184). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Bismack, A. S., Arias, A. M., Davis, E. A., & Palincsar, A. S. (2015). Examining student work for evidence of teacher uptake of educative curriculum materials. *Journal of Research in Science Teaching, 52*(6), 816–846.

Bonney, R., Ballard, H., Jordan, R., McCallie, E., Phillips, T., Shirk, J., & Wilderman, C. C. (2009). *Public participation in scientific research: Defining the field and assessing its potential for informal science education*. A CAISE inquiry group report. Washington, DC: Center for Advancement of Informal Science Education (CAISE).

Bonney, R., & Dickinson, J. L. (2012). Overview of citizen science. In, J. L. Dickinson & R. Bonney (Eds.), *Citizen Science: Public Participation in Environmental Research* (pp. 19-26). New York: Cornell University Press.

Bonney, R., Phillips, T., Ballard, H. L., & Enck, J. W. (2015). Can citizen science enhance public understanding of science? *Public Understanding of Science*, 1-15.

Cherif, A. H. (1992). Barriers to ecology education in North American high schools: Another alternative perspective. *The Journal of Environmental Education, 23*(3), 36-46.

Clarke, J., & Dede, C. (2009). Design for scalability: A case study of the River City curriculum. *Journal of Science Education and Technology, 18*, 353–365.

Davis, E. A., Palincsar, A. S., Arias, A. M., Bismack, A. S., Marulis, A. M., & Iwashyna, S. K. (2014). Designing educative curriculum materials: A theoretically and empirically driven process. *Harvard Educational Review, 84*(1), 24–53.

Deveci, İ., & Karteri, İ. (2020). Context-Based Learning Supported by Environmental Measurement Devices in Science Teacher Education: A Mixed Method Research. *Journal of Biological Education*, 1-26.

Dickinson, J. L., & Bonney, R. (2012). Introduction: Why citizen science. 1-14. In J. L. Dickinson & R. Bonney (Eds.). *Citizen science: Public participation in environmental research* (pp.1-14). Ithaca, New York: Cornell University Press.

Drayton, B., & Falk, J. (2006). Dimensions that shape teacher-scientist collaborations for teacher enhancement. *Science Education, 90*(4), 734-761.

Doubler, S. J. (1997). Two-way partnerships: An introduction to SSPs. In *National Conference on Student &Scientist Partnerships* (pp. 23 – 26). Cambridge, MA: TERC and Concord Consortium.

Edelson, D. C. (2002). Design research: What we learn when we engage in design. *Journal of the Learning Sciences, 11*(1), 105–121.

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences, 8*(3–4), 391–450.

Edelson, D. C., & Reiser, B. J. (2006). Making authentic practices accessible to learners: Design challenges and strategies. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 335–354). New York: Cambridge University Press.

Emerson, R. M., Fretz, R. I., & Shaw, L. L. (1995). *Writing ethnographic fieldnotes*. Chicago: The University of Chicago Press.

Ertmer, P. A., & Quinn, J. (2007). *The ID case book: Case studies in instructional design (3rd edition)*. New Jersey: Pearson.

Finkelstein, N. (2015). Learning physics in context: A study of student learning about electricity and magnetism. *International Journal of Science Education, 27*(10), 1187-1209.

Foss, A. W., & Ko, Y. (2019). Barriers and opportunities for climate change education: The case of Dallas-Fort Worth in Texas. *The Journal of Environmental Education*, *50*(3), 145-159.

Gilbert, J. K. (2006). On the nature of "context" in chemical education. *International Journal of Science Education, 28*(9), 957-976.

Gilbert, J. K., Bulte, A. M. W., & Pilot, A. (2011). Concept development and transfer in context-based science education. *International Journal of Science Education, 33*(6), 817-837.

The Globe Program (n.d.), Retrieved on May 20, 2019, from https://www.globe.gov/do-globe/classroom-ready-activities/learning-activities

Goodlad, J., Klein, M., & Tye, K. (1979). The domains of curriculum and their study. In J. Goodlad & Associates (Eds.), *Curriculum inquiry: The study of curriculum practice* (pp. 43–76). New York: McGraw-Hill.

Gray, S. A., Nicosia, K., & Jordan, R. C. (2012). Lessons learned from citizen science in the classroom. Democracy & Education, 20(2), 1-5.

Gustafson, K. L., & Branch, R. (2002). *Survey of instructional design models* (4th ed). Syracuse University: ERIC Clearinghouse on Information Resources.

Guba, E. G. (1981). Criteria for assessing the trustworthiness of naturalistic inquiries. *Educational Communication and Technology, 29*(2), 75-91.

Harlin, J., Kloetzer, L., Patton, D., Leonhard, C., & Leysin American School high school students. (2018). Turning students into citizen scientists. In S. Hecker, M. Haklay, A. Bowse, Z. Makuch, J. Vogel, & A. Bonn (Eds.), *Citizen Science: Innovation in Open Science, Society and Policy* (pp. 410-428). UCL Press: London.

Holmqvist Olander, M., & Olander, C. (2017). Understandings of climate change articulated by Swedish secondary school students. *Journal of Biological Education*, *51*(4), 349-357.

Houseal, A. K., Abd-El-Khalick, F., & Destefano, L. (2014). Impact of a student-teacher-scientist partnership on students' and teachers' content knowledge, attitudes toward science, and pedagogical practices. *Journal of Research in Science Teaching, 51*(1), 84-115.

Howard, C. D., Boling, E., Rowland, G., & Smith, K. M. (2012). Instructional design cases and why we need them. *Educational Technology*, *52*(3), 34.

Jordan, R. C., Ehrenfeld, J. G., Gray, S. A., Brooks, W. R., Howe, D. V., & Hmelo-Silver, C. E. (2012). Cognitive considerations in the development of citizen science projects. In J. L. Dickinson, & R. Bonney (Eds.), *Citizen Science: Public*

Participation in Environmental Research (pp. 167–178). Ithaca, NY, USA: Cornell University Press.

Kelemen-Finan, J., Scheuch, M., & Winter, S. (2018). Contributions from citizen science to science education: An examination of a biodiversity citizen science projects with schools in Central Europe. *International Journal of Science Education, 40*(17), 2078 - 2098.

Krajcik, J. S., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education*, *92*(1), 1–32.

McLaughlin, C. A., Broo, J., MacFadden, B. J., & Moran, S. (2016). Not looking a gift horse in the mouth: exploring the merits of a student–teacher–scientist partnership. *Journal of Biological Education*, *50*(2), 174-184.

Merriam, S. B. (1988). *Case study research in education: A qualitative approach*. Jossey-Bass.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook.* Thousand Oaks, California: Sage.

Monroe, M. C., Plate, R. R., Oxarart, A., Bowers, A., & Chaves, W. A. (2019). Identifying effective climate change education strategies: a systematic review of the research. *Environmental Education Research*, *25*(6), 791-812.

NGSS Lead States (2013). *Next Generation Science Standards: For States, By States.* Washington, DC: The National Academies Press.

Paige, K., Hattam, R., & Daniels, C. B. (2015). Two models for implementing citizen science projects in middle school. *Journal of Educational Enquiry, 14*(2), 4-17.

Phillips, T., Porticella, N., Constas, M., & Bonney, R. (2018). A framework for articulating and measuring individual learning outcomes from participation in citizen science. *Citizen Science: Theory and Practice, 3*(2), 3.

Pilot, A., & Bulte, A. M. W. (2006). The use of "contexts" as a challenge for the chemistry curriculum: Its successes and the need for further development and understanding. *International Journal of Science Education, 28*(9), 1087-1112.

Rose, D. E. (2012). Context-based learning. In N. Seel (Ed.). Encyclopedia of the Sciences of Learning (pp. 799-802). New York: Springer.

Roseman, J. E., Herrmann-Abell, C. F., & Koppal, M. (2017). Designing for the Next Generation Science Standards: Educative curriculum materials and measures of teacher knowledge. *Journal of Science Teacher Education, 28*(1), 111-141.

Schwartz, A. T. (2006). Contextualized chemistry education: The American experience. *International Journal of Science Education, 28*(9), 977 – 998.

Shah, H. R., & Martinez, L. R. (2016). Current approaches in implementing citizen science in the classroom. *Journal of Microbiology & Biology Education*, *17*(1), 17–22.

Songer, N. B. (2006). BioKids: An animated conversation on the development of curricular activity structures for inquiry science. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 355–369). New York: Cambridge University Press.

Thijs, A., & van den Akker, J. (2009). *Curriculum in development*. Enschede, The Netherlands: SLO Netherlands Institute for Curriculum Development.

Trautmann, N. M., Shirk, J., Fee, J., & Krasny, M. E. (2012). Who poses the question? Using citizen science to help K–12 teachers meet the mandate for inquiry. In J. L. Dickinson, and R. Bonney (Eds.), *Citizen science: Public collaboration in environmental research* (pp. 179 – 190). Ithaca, NY: Cornell University Press.

Valero Haro, A., Noroozi, O., Biemans, H. J., & Mulder, M. (2019). The effects of an online learning environment with worked examples and peer feedback on students' argumentative essay writing and domain-specific knowledge acquisition in the field of biotechnology. *Journal of Biological Education*, *53*(4), 390-398.

van den Akker, J. (2003). Curriculum perspectives: An introduction. In J. Van den Akker, W. Kuiper, & U. Hameyer (Eds.), *Curriculum landscapes and trends* (pp. 1–10). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Van Gog, T., Paas, F., & Merriënboer, J. J. (2004). Process-oriented worked examples: Improving transfer performance through enhanced understandings. *Instructional Science*, *32*(1), 83–98.

Yin, R. K. (2014). *Case study research: Design and methods* (5th edition). Thousand Oaks, California: Sage Publications, Inc.

Yu, K. C., Fan, S. C., & Lin, K. Y. (2015). Enhancing students' problem-solving skills through context-based learning. *International Journal of Science and Mathematics Education*, *13*(6), 1377-1401.

Zangori, L., Forbes, C. T., & Biggers, M. (2013). Fostering student sense making in elementary science learning environments: Elementary teachers' use of science curriculum materials to promote explanation construction. *Journal of Research in Science Teaching*, *50*(8), 989–1017.

Zoellick, B., Nelson, S. J., & Schauffler, M. (2012). Participatory science and education: Bringing both views into focus. *Frontiers in Ecology and Environment, 10*(6), Citizen Science – new pathways to public involvement in research, 310-313.

Chapter 5
Boundary Crossing

Student-Teacher-Scientist Partnerships (STSPs) provide opportunities for students and teachers to participate in citizen science and engage with scientific concepts and practices, thereby bridging school learning with issues of importance to society, such as climate change. But STSPs require partners to cross boundaries between the cultures of science and schooling, which is extremely difficult. This three-year case study illuminates how successful designers tackled boundary crossing challenges while creating a scalable STSP for environmental education. Analysis of data gathered from three sources – designer-generated documents, interviews with designers, and researchers' observations of the designer work - through an in-depth participant-observation approach revealed how designers (curriculum writers and partner ecologists) made it possible for middle school students and teachers from partner schools to contribute climate-related data to the ecologists' research and to other citizen science programs, while accommodating teacher preferences and curricular constraints to pursue educational goals. Findings about how designers used specific methods and created curriculum supports to aid processes of boundary crossing are discussed in light of relevant literature, highlighting their considerations about specific stakeholder needs related to pedagogical, curricular, and scientific goals of the partnership. Further, distilled from the empirical findings and in light of relevant literature are three guidelines in designing for STSPs to foster student inquiry, to support teachers, and to provide multiple benefits through the STSP. These findings and guidelines can help designers anticipate and attend to boundary crossing challenges in STSPs designed for environmental education, with broader implications for science education in general.

This chapter is based on:

Bopardikar, A., Bernstein, D., & McKenney, S. (in press). Boundary crossing in student-teacher-scientist-partnerships: Designer considerations and methods to integrate citizen science with school science. *Instructional Science*.

Citizen science initiatives enable non-scientists as members of the general public to partner with professional scientists and participate in organized scientific research, for which they may gather and analyze large amounts of data and report findings (Bonney, Ballard, Jordan, McCallie, Phillips, Shirk, & Wilderman, 2009; Bonney, Phillips, Ballard, & Enck, 2015), often focused on environmental matters (Dickinson & Bonney, 2012). The term citizen science itself is a more recent coinage within a much older tradition of public engagement in science that dates back to the 1800s (Bonney et al., 2015; Dickinson & Bonney, 2012). Owing to their potential to engage non-scientists in developing scientific knowledge, citizen science projects have gained popularity around the globe in promoting science learning (e.g., Aivelo & Huovelin, 2020; Harlin, Kloetzer, Patton, Leonhard, & Leysin American School high school students, 2018; Kelemen-Finan, Scheuch, & Winter, 2018; National Academies of Sciences, Engineering, and Medicine, 2018; Paige, Hattam, & Daniels, 2015; Sagy, Kali, Hod, Baram-Tsabari, Tal, & Ben-Zvi, 2020). Although commonly implemented in informal science educational settings, citizen science can move into school classrooms within formal science education programs, where teachers play a pivotal role in integrating citizen science projects with their science curricula (Roche, Bell, Galvão, Golumbic, Kloetzer, Knoben, Laakso, et al., 2020).

The present study, conducted in the United States, focuses on student-teacher-scientist partnerships (STSPs) as a specific model for integrating citizen science with science learning in formal precollege education (see Zoellick, Nelson, & Shauffler, 2012 for a similar conceptualization of STSPs and school-based citizen science). Whereas student and scientist partnerships have existed for a long time in higher education and in other scientific research settings, the potential of designing such partnerships for K-12 school settings came to the fore in the 1990s to serve the learning needs of all students (Morse, 1997). STSPs provide a formal arrangement in which students and teachers collaborate closely with scientists to "answer real-world questions about a phenomenon or problem the scientists are studying" (Houseal, Abd-El-Khalick, & Destefano, 2014, p. 86), thus presenting opportunities to bridge school science with pertinent issues in students' everyday lives and society, such as climate change. In so doing, students and teachers gain first-hand exposure to scientific practices, while scientists can enlist students' help in gathering data to answer pressing scientific questions (Doubler, 1997). The partnership is driven by mutual goals of scientific knowledge construction and benefits for both science education and scientific research (Morse, 1997).

In this paper, we use the term *citizen science* to refer broadly to public participation in scientific research (Phillips, Porticella, Constas, & Bonney, 2018) and the term *STSP* to refer narrowly to the more direct collaboration between K-12 school partners and scientists as they work together on scientific research. This distinction is based on the degree of direct interactions and negotiations between scientists and school partners. In STSPs, the school partners typically receive more direct support from the scientists, and the needs of different stakeholders require careful negotiation to serve both specific learning outcomes for school partners and scientific outcomes related to the scientists' research (He & Wiggins, 2017; Houseal et al., 2014; Zoellick et al., 2012). Although some citizen science projects include previously developed resources and training workshops that can be used by subsequent groups of school partners to serve stand-alone or larger projects, the extent to which students and teachers interact directly with scientists and to which student-gathered data are actually used for scientific research are variable and in some cases unclear (Trautmann, Shirk, Fee, & Krasny, 2012; Bonney et al., 2015; He & Wiggins, 2017).

5.1 Rationale of the study

5.1.1 Benefits and challenges in designing for STSPs: Crossing boundaries between science and schooling

Studies indicate that STSPs offer various benefits for students, teachers, and scientists. For example, students have shown gains in their knowledge of scientific concepts and skills (Golumbic, Baram-Tsabari, & Fishbain, 2016; Hedley, Templin, Czajkowski, & Czerniak, 2013), increased positive attitudes towards scientists (Houseal et al., 2014), and development of agency in using environmental science to take action towards conservation (Ballard, Dixon, & Harris, 2017). Studies also reveal positive shifts in teachers' pedagogical choices, such as increasingly supporting students to communicate their understanding and to apply concepts and make connections in various content areas (Houseal et al., 2014). Scientists, too, gain insights into the realities of schools and ideas for public outreach (Drayton & Falk, 1997, 2006).

While STSPs hold promise, differences in the cultures of science and schooling present boundaries which can disrupt the collaboration. In addition to organizational boundaries, there are other salient differences between these communities of practice. For example, teachers bring to their practice broad content knowledge and are tasked with nurturing interest among their students, all the while working in resource-limited settings. On the other hand, scientists draw on specialized knowledge of their subject, and bring high levels of intrinsic motivation to their practice in settings characterized by a greater access to scientific and scholarly resources (Tanner, Chatman, & Allen, 2003). Another difference exists in terms of the duration of research projects. Student projects typically last days or weeks, while scientific research often extends over years or decades (Barstow, 1997), making it difficult to obtain meaningful scientific findings in short time periods, which are crucial to maintaining student interest. And although common goals undergird the collaboration, scientists are often concerned with the validity of (student-generated) data for scientific research, while teachers are often concerned with the alignment of the collaboration with educational standards (Doubler, 1997).

Additionally, to advance scientific knowledge, student participation in data collection may be overemphasized at the expense of other scientific practices such as data analysis. However, standardized data collection protocols may be implemented selectively and with interruption in schools due to curricular requirements and time constraints, yielding incomplete and inconsistent data with reduced scientific value (Means, 1998). The resulting low quality of student-gathered data, despite the provision of simple methods and detailed protocols, thus necessitates specialized in-person or remote trainings for school partners prior to fieldwork (Castagneyrol, Valdés-Correcher, Bourdin, Barbaro, Bouriaud, et al., 2019).

Further, the background knowledge required to understand scientists' research may be too far in advance of the students' and teachers' understanding (Drayton & Falk, 1997, 2006). This is complicated by the fact that many schools must adhere to topics specified in their curricula and assessments (Moreno, 2005), whereas scientists focus on topics relevant to (sometimes rapidly changing) real-world issues. As a result, scientist partners are tasked with identifying content that will engage students in real-world problems while developing their understanding of the fundamental concepts and practices that will be assessed in schools (Moreno, 2005). Finally, direct interactions with scientists and clarity on using student-generated data for science are important to sustain the interest of school partners, but such interactions are time-intensive for scientists and need careful orchestration (Means, 1998).

More recent literature also highlights similar and additional issues (see Roche et al., 2020). For example, in addition to curricular and scheduling constraints, teachers are tasked with nurturing engagement among students who may lack motivation to participate in the project. This contrasts with general citizen science projects in which the participation of non-scientists is voluntary. And it is especially difficult when teachers lack the content knowledge to facilitate students' fieldwork. Finally and more pertinent to recent times, with the rapid explosion of citizen science initiatives over the last two decades, teachers may struggle to choose among available options that would enable them to align scientific goals and needs of the projects with specific educational goals and needs of their own settings.

5.1.2 Problem statement

To address these issues, it seems clear that STSPs must be designed to help all partners acquire insight into work outside of their own domains, a practice referred to as boundary crossing (Tsui & Law, 2007). In crossing boundaries, individuals seek to establish actions or interactions across practices of collaborating sites that are characterized by different norms, goals, tools, etc. (Bakx, Bakker, Koopman, & Beijaard, 2016). In the context of STSPs, this means that students, teachers, and scientisist collaborate across the domains of school and scientific research, bringing to bear their own interests, focus, and expertise as shaped by those domains, while pursuing mutually agreed upon objectives.

Specifically, it is vital that partners in STSPs understand the needs and goals of various stakeholders, so that students and teachers can cross boundaries from school practice into scientific research. By coming to understand better the aims and methods of the scientific research program, which may be less easily accessible initially to students and teachers, the school partners can contribute towards it directly by gathering, analyzing, and reporting specific kinds of data. Similarly, understanding stakeholders is important to help scientists cross boundaries in the other direction from scientific research into school science education. By coming to understand better the needs and requirements of their school partners, which may be less familiar initially to the scientists, they can contribute towards intentionally fostering students' interest and content knowledge. Through crossing boundaries between the domains of scientific research and science education, signifying respectively science as practised by professional scientists to construct knowledge and instructing students in those practices, STSPs can thus contribute towards developing scientific knowledge through the participation of non-scientists, while making scientific knowledge more accessible to the public to nurture their motivation, understanding, and action for urgent real-world problems, such as climate change.

Nonetheless, this presents a tremendous challenge to the designers of STSPs, especially because citizen science is still a nascent approach to supporting science learning in schools. While current literature describes boundary crossing processes (Akkerman & Bakker, 2011) and offers guidelines for school and scientist partnerships in general (Houseal et al., 2014; Moreno, 2005), designers of STSPs also require additional information to integrate citizen science with school science. For example, how might designers equip students with the requisite knowledge and skills to contribute to scientific research, and how might they support teachers to help students towards this end (Zoellick et al., 2012)? How might designers select sites for engaging fieldwork when faced with typical school constraints of safety, transportation, and permissions for field visits (He & Wiggins, 2017)? And how might designers promote student ownership of scientific investigations while balancing the needs of teachers and scientists (Houseal et al., 2014)? Further, how might technology be leveraged to help STSPs bridge school science learning with scientific issues of importance to society? Finally, it is vital that curricula support inquiry centered on phenomena of interest to students. But for productive inquiry, students also need motivation to proceed from immediate (ecological) phenomena and connect with global phenomena and more abstract concepts (Feldman, Konold, & Coulter, 2000). How might designers then foster and reinforce local-distant connections through both in-class and fieldwork experiences?

5.1.3 Study goal and significance

The current literature contains some (limited) guidance for STSP designers. For example, designers working across contexts can be informed by research on processes of boundary crossing in different domains of education and work (Akkerman & Bakker, 2011). Additionally, research reports general activities and supports for school and scientist partnerships, the challenges therein, and their outcomes (Houseal et al., 2014; Moreno, 2005). There are also generic models describing methods for instructional design (Gustafson & Branch, 2002) and curriculum design (Thijs & van den Akker, 2009). Finally, there is general guidance available through case studies for teaching instructional design (Ertmer & Quinn, 2007). However, what is lacking are detailed, empirically-derived and theoretically-informed insights into designer considerations and actions for integrating citizen science with school science and for supporting STSP stakeholders to cross boundaries in the mutual pursuit of scientific and educational goals.

Therefore, this study aimed to produce a detailed example of how designers of STSPs perform their work in bringing citizen science to schools and thereby bridging formal science learning with relevant issues in students' local environments and the broader society. Like process-oriented worked examples in other areas (Van Gog, Paas, & Merriënboer, 2004), the present example delineates designer thinking and key methods in tackling important considerations, as exemplified in an emergent STSP design for environmental education. In so doing, the study provides a vital precedent articulating underlying designer rationales and processes (Howard, Boling, Rowland, & Smith, 2012) to aid other designers in understanding and attending to challenges in designing for STSPs.

5.1.4 Context of the study

To tackle questions like these and support the development of future STSPs, a prolonged case study involving a participant-observation approach investigated the evolution of designer thinking and action while designing for a successful STSP for middle schools to promote education about climate change (see Method for more details). To this end, the investigation focused squarely on unpacking the rationales and measures taken by curriculum writers and partner ecologists because they actively created various curriculum supports for the STSP. Further, as evidenced in the findings, the designers attended to the needs and outcomes of students and teachers in creating these supports, but the school partners did not participate in this study, a point which we revisit in the Discussion section. While this specific case is situated in the USA, designers in international contexts may experience similar challenges to those documented here, and thus also benefit from the insights related to designing for STSPs to integrate citizen science with school science in serving environmental education goals.

Finally, as elaborated in the Methods, Results, and Discussion sections, the ecologists and teachers were both the intended end users of the STSP and stakeholders in developing the partnership. The ecologists (together with curriculum writers) attended to educational and scientific goals and needs, and they contributed ideas and outputs in actively creating various curriculum supports, while the teachers implemented and provided feedback at various points in the design process. Although not a complete representation of participatory design per se, the present case can illuminate how the expertise and experiences of multiple stakeholders are brought together. Used in the field of design more broadly (Baek, Kim, Pahk, & Manzini, 2018; Cipolla & Manzini, 2009; Mosley, Markauskaite, & Wrigley, 2021; Sanders & Stappers, 2008) and in the field of educational design more specifically (Könings, Seidel, & Van Merriënboer, 2014; Penuel, Fishman, Cheng, & Sabelli, 2011), participatory design approaches involve intense collaboration and engagement between professional designers and users from non-design backgrounds to yield high quality usable innovations that are more likely to be accepted, better understood, and effectively implemented in practice (Könings, Brand-Gruwel, & Van Merriënboer, 2007). Such approaches are especially crucial for producing educational interventions because professional designers, practitioners, and students often bring different perspectives to teaching and learning, and a lack of congruence among the perspectives may impede intervention implementation and effectiveness (Könings et al., 2014).

In following participatory approaches, designers are tasked with facilitating dialogue and problem-solving among stakeholders as they collaborate across boundaries of practice (Mosley et al., 2021). For designers wishing to create STSPs through participatory approaches, however, greater clarity is needed on issues such as the following: How can teachers and scientists be supported to contribute during the design process? What activities and tools are used to facilitate communication between school partners and scientists? Finally, how are potential or actual student perceptions and experiences of the intervention accounted for in the emerging design? The present case provides insights to tackle such questions.

5.1.5 *Conceptual framework*

As mentioned before, teachers and partner ecologists served as stakeholders in the design process to create the present STSP. The study investigated more specifically how designers attend to three crucial dimensions in creating STSPs: (i) supporting stakeholders (school partners and scientists) in STSPs to understand one another's needs and wishes in relation to boundary crossing processes; (ii) producing curricular supports to help stakeholders engage in the boundary crossing processes; and (iii) employing specific methods during key phases of curriculum design for creating the curricular supports to aid boundary crossing processes. Previewed in Figure 5.1 and elaborated in the remainder of this section, the conceptual framework guiding the study highlights crucial dimensions of STSP designer work, and was synthesized from the wider literature on science education, STSPs, boundary crossing, and curriculum and instructional development and design processes.

The framework focuses on these three dimensions (and not others) because the dimensions together provide a specific and concise structure to systematically investigate and articulate designer rationales and measures that result in specific educational designs. This is consistent with the goal of the study and with calls in instructional design more broadly to relate processes and decisions directly to finished designs (Howard et al., 2012). Designing and thus understanding educational interventions requires detailed consideration of the needs and context

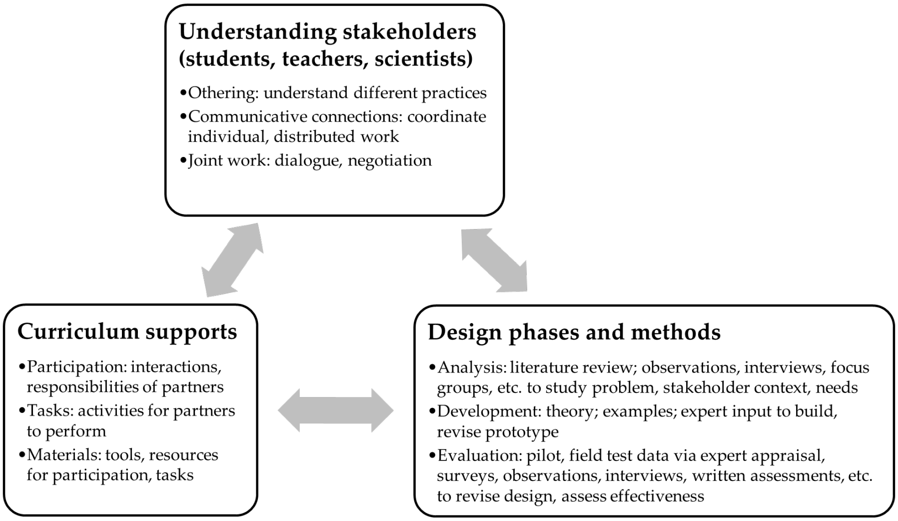


Figure 5.1: Conceptual framework highlighting crucial dimensions of STSP designer work.

of the target users, which in the case of STSPs focuses on the school and scientist partners who are key stakeholders in enacting the partnerships. Furthermore, designer ideals and vision are often embodied in (curricular) products to help end users implement the interventions, thus also requiring a careful analysis of the form of the design. Finally, crucial to understanding any educational design is to unpack the choices made and actions taken by its designers to overcome challenges, address tensions, and tackle trade-offs in creating specific design forms.

The dimensions of the present framework are derived from three classic perspectives discussed in curriculum design theory (Goodlad, 1994). The socio-political perspective refers to the values, interests, and influence of various stakeholders (e.g., students, parents, teachers, curriculum developers, etc.) and serves as a point of departure for the first dimension focused on sensitizing students, teachers, and scientists to one another's concerns through specific boundary crossing processes. The substantive perspective attends to the planned and enacted curriculum, including goals, subject matter content, and tools and materials, and can include the usability of the intervention. This perspective relates to the second dimension focused on what STSP designers create and how these designs support boundary crossing in service of learning, teaching, and conducting science. Finally, the technical-professional perspective focuses on methods of engineering, logistics, testing, and refinement for manifesting ideas into specific designs. This perspective is related to the third dimension focused on designer methods during phases of design to iteratively yield the STSP.

5.1.6 Understanding stakeholders

Central to STSP design work is (coming to) understand the needs and wishes of the students, teachers, and scientists involved, and helping them to understand each other's perspectives in crossing boundaries between the cultures of science and schooling. Three processes that have been described in boundary crossing literature (Akkerman & Bakker, 2011) are particularly relevant to STSPs for integrating citizen science with school science. First, *othering* concerns activities through which individuals come to understand the different practices of the collaborating sites. In STSPs, othering could take place when partners examine specific scientific practices for gathering and analyzing data for scientific research purposes, alongside the standards-based content that is specified in science education frameworks with which teachers and students are expected to engage. Whereas the process of othering as defined in the literature emphasizes differentiating explicitly among practices of collaborating sites (Akkerman & Bakker, 2011), the present study focuses on how othering manifests in designer work to help school partners and scientists understand how each other's work is framed by specific needs and expectations, especially in relation to the curricular goals pursued by schools and the specialized knowledge that underlies scientific research, as noted previously in the sub-section on challenges in designing for STSPs. That is, the study unpacks how stakeholders are supported to understand the standards-aligned science content that frames school instruction and the actual research and practices of local scientists, and how these relate to one another.

Second, to ensure sufficient cooperation, it is important that stakeholders establish *communicative connections* so that individual and distributed work through routinized exchanges and dialogue remains coordinated. This process can be performed via boundary objects (e.g., standardized forms and diagrams) or standardized procedures for gathering and recording of information by amateurs (Carlile, 2002; Star & Griesemer, 1989). For example, student-generated data captured on standardized data sheets or represented in graphs and tables serve as boundary objects between fieldwork orchestrated by teachers and the scientists' research institution, thus facilitating a communicative connection between partners.

Third, designers need to ensure that STSP participants are prompted to engage in *continuous joint work,* which provides focus and relevance to their dialogue and negotiation of meaning. To facilitate joint endeavors in STSPs, platforms for communication between teachers and scientists may include online sessions (Means, 1998) and in-person workshops and electronic discussion boards and conferences (Houseal et al., 2014). This may enable scientists to help teachers learn specific science content and tools and change their instructional practice in turn. And teachers may provide feedback to negotiate proposed joint activities, such as modifications to data collection protocols to suit students' abilities while satisfying scientists' criteria for reliable data.

5.1.7 *Curriculum supports*

STSP designers create supports within the curriculum to facilitate the boundary crossing processes described before. In so doing, designers must ensure that students are sufficiently equipped to perform basic scientific work while aligning their action with both scientists' questions and the learning outcomes specified in curriculum frameworks (Zoellick et al., 2012). Further, curricular supports must make relevant scientific information available for student reading and critique, and facilitate ongoing dialogue with scientists to help students and teachers develop, refine, and conduct school-based investigations (Gray et al., 2012). While educational designers attend to myriad details, most of them relate to participation, tasks, and materials (McKenney & Reeves, 2019; Sandoval, 2014).

5.1.7.1 Participation

Designers develop and articulate a vision for *participation,* i.e., how students, teachers, and scientists will interact with one another, and the roles and responsibilities they will perform during the partnership. For example, in STSPs, students may be expected to collaborate during fieldwork, and to gather and share specific samples of data. The envisioned teacher role may include providing feedback to scientists about the feasibility of the fieldwork tasks and protocols (Houseal et al., 2014). Further, scientists may be expected to communicate standardized methods of data collection with students and teachers (Saunders, Roger, Geary, Meredith, Welbourne, Bako, et al., 2018), respond to questions, share relevant information, and include student-generated findings in their dissemination efforts (Bonney & Dhondt, 1997).

5.1.7.2 Tasks

Designers also create the *tasks*, or learning activities, in which students (often together with teachers and/or scientists) are expected to participate during the partnership. The envisioned tasks may involve student projects organized around driving questions (Condliffe, Qunit, Visher, Bangser, Drohojowska, Saco, et al. 2017) and participate in class discussions to construct scientific explanations (Novak & Treagust, 2017). Sample tasks for students in STSPs include generating scientific questions, conducting fieldwork to gather data based on specified protocols, and analyzing and reporting findings in different communities (Houseal et al., 2014). Tasks for teachers in STSPs are attending professional development sessions aimed at helping students generate suitable scientific questions and interpret data (Zoellick et al., 2012). Finally, sample tasks for scientists are formulating questions, research design, and logistics of implementing citizen science projects on school sites (Saunders et al., 2018), participating in online and/or in-person meetings with teachers (and students) to clarify science content and to conduct fieldwork (Houseal et al., 2014; Kelemen-Finan, Scheuch, & Winter, 2018), and teaching classroom-based lessons on specific concepts and practices through interactive exercises and discussions (Miczajka, Klein, & Pufal, 2015).

5.1.7.3 Materials

Finally, designers create *materials to* support the learning activity in ways that align with the envisioned participation. These include digital and/or analogue tools and resources, such as books, guides, and communication media that enable students, teachers, and scientists to perform specified tasks. Student materials may include written prompts to facilitate data analyses (Songer, 2006). Teacher materials may present learning objectives and desired student responses (Schwartz, 2006), definitions of and rationales for scientific practices (McNeill, González-Howard, Katsh-Singer, & Loper, 2017), educative notes explaining students' typical ideas about scientific concepts (Roseman, Hermann-Abell, & Koppal, 2017), and strategies to engage students in scientific practices (Bismack, Arias, Davis, & Palincsar, 2015). Sample STSP materials are fieldwork protocols and worksheets containing stepwise instructions about scientific practices (The Globe Program), and lesson plans and teacher guides providing inquiry-based strategies (Trautmann, Shirk, Fee, & Krasny, 2012). Finally, the teacher guides may include personal messages from the scientists for motivating school partners to sustain their investigations (Means, 1998).

5.1.8 Design phases

Educational designer decision-making is a dynamic process which unfolds through iterative phases, each of which features activities and deliberation to realize the underlying vision (Branch & Merrill, 2012; Gustafson & Branch, 2002; McKenney & Reeves, 2019). As van den Akker (2013, p. 56) describes, it is "usually a long and cyclical process with many stakeholders and participants; in which motives and needs for changing the curriculum are formulated; ideas are specified in programmes and materials; and efforts are made to realize the intended changes in practice." While the sequence and duration of the process vary with each project, three main phases are well-described in instructional and curriculum design literature: analysis, development, and evaluation.

5.1.8.1 Analysis

Designers typically begin with this phase, in which they study the problem (Thijs & van den Akker, 2009) and analyze the needs of the target audience (Edelson, 2002; McKenney & Reeves, 2019). The main methods used in this phase include reviewing the literature to explore how other designers have understood and responded to similar problems and gathering data about the target context and stakeholders. The literature review may focus on learning theories and prior curriculum materials and research to foster teacher knowledge (Kruse et al., 2013; Roseman et al., 2017). The data about context and stakeholders' needs, wishes, existing practice, and challenges may be gathered through survey questionnaires about their perceptions of the problem and possible solutions (Akomaning, 2019) and through interviews, observations, instructional logs of existing curriculum use (Davis, Palincsar, Arias, Bismack, Marulis, & Iwashyna, 2014). Accordingly, the tasks and participation structures are envisioned, and preliminary design requirements and specifications are generated to plan the materials. For example, designers analyze ways to balance the research needs of scientists with classroom constraints voiced by teachers, and students' interests in contributing to authentic scientific research (Zoellick et al., 2012). They may also inventory existing needs to be addressed by the curriculum supports. For example, a common teacher need is addressing gaps in their own knowledge of specific scientific concepts and relevant scientific practices to support their students' learning (Drayton & Falk, 1997, 2006).

5.1.8.2 Development

In this phase, designers specify the tasks, materials, and participation structures, and construct and revise prototypes of these elements based on inputs from both the analysis phase and the subsequent evaluation phase (McKenney & Reeves, 2019). The main methods include reviewing theory and inspiring examples to derive specific ideas and gathering input from local expertise (McKenney & Reeves, 2019), such as from scientists (Edelson, Gordin, & Pea, 1999; Songer, 2006) and from teachers to frame science content in real-world contexts (Rivet & Krajcik, 2004). For example, scientists may help identify specific content for which student-gathered data are crucial to advance scientific knowledge while also developing students' own understanding (Means, 1998). Throughout this phase, designers fine-tune both their vision and the materials intended to support the enactment of tasks according to the envisioned participation structures (McKenney & Reeves, 2019). They also return to this phase after conducting additional analyses or evaluating (prototype) designs.

5.1.8.3 Evaluation

In this phase, data are gathered to inform subsequent revisions to the tasks, materials, and participation structures, and to assess their effectiveness (Branch & Merrill, 2012; Gustafson & Branch, 2002). The main methods include conducting pilots of early prototypes and field tests of more mature versions of the design to generate various sources of data for formative and summative evaluation (McKenney & Reeves, 2019). For example, designers may appraise the accuracy of the science content highlighted in the materials from external experts (Davis et al., 2014), observe student engagement (Edelson et al., 1999), examine student understanding through written assessments (Clarke & Dede, 2009) and interviews (Wiser, Smith, & Doubler, 2012), and obtain in-person or survey-based feedback from teachers, such as on fieldwork protocols (Houseal et al., 2014). Following this phase, designers often return to the development phase to revise the design elements.

Based on the preceding conceptual framework and literature review, the following study question was formulated to attain the goal of generating an in-depth understanding of designer work that is grounded in empirical findings and informed by the wider literature, and to offer insights in designing for STSPs to integrate citizen science with school science:

How do designers attend to stakeholders' (i.e., students', teachers', and scientists') needs, what curriculum supports do they create, and what methods do they employ during phases of the design process in designing for STSPs to integrate citizen science with school science?

5.2 Method

5.2.1 Study approach

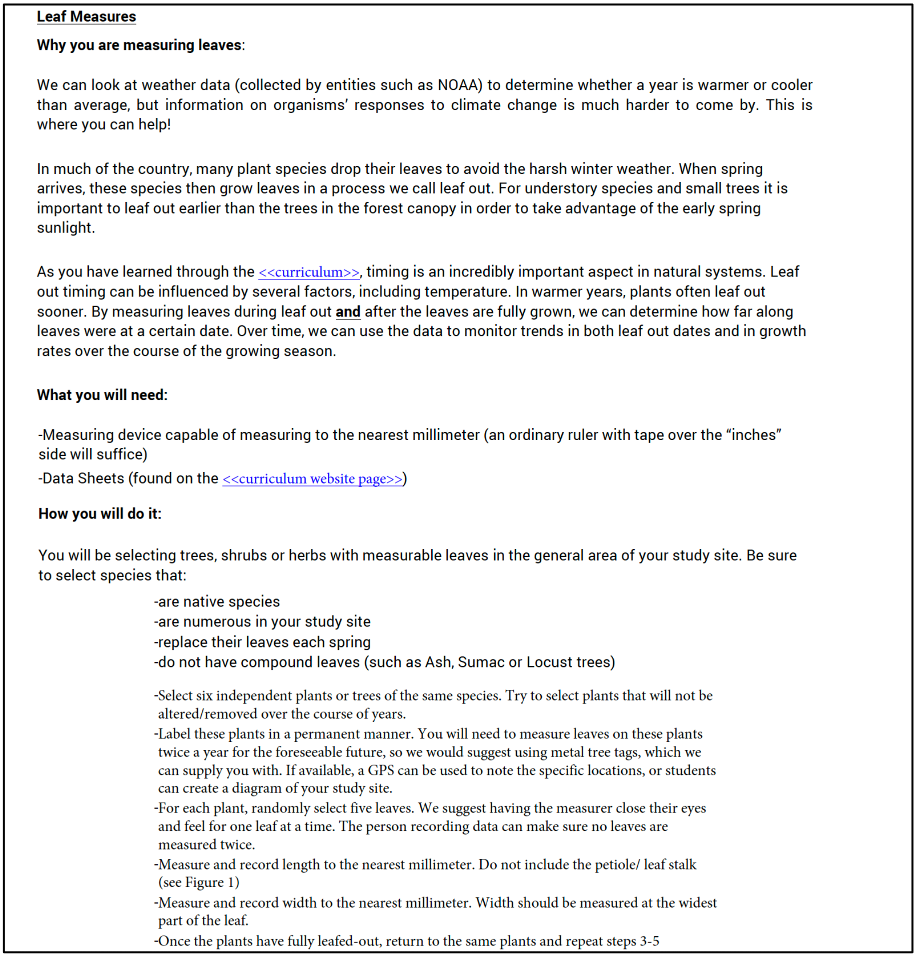
To answer the study question, a qualitative interpretive case study (Merriam, 1988) was conducted using a participant-observation approach, which helped capture phenomena that are generally challenging to investigate deeply (Yin, 2014). This approach was chosen because the desired product was a detailed articulation of designer rationales and activities behind specific designs (Howard et al., 2012), in this case, a single successful STSP.

The present STSP involved ecologists investigating climate change at a scientific research institution in the United States and students and teachers from local middle schools contributing climate-related data to the ecologists' research. The STSP was part of a mandate for outreach by the scientific research institution. The shared goal was "linking the science classroom with current science research being conducted by field stations and other scientific institutions," thus "bringing science research closer to the science classroom." As mentioned in their grant proposal, the STSP aimed to provide students with opportunities to experience key scientific practices through data collection on local sites and analyses of their own as well as other existing data sets. In so doing, it was hoped that students would develop "interest in and engagement with science" and "gain a better understanding of science as practiced." The grant proposal also stated that the STSP was warranted by research on the potential of citizen science for science education, and it intended to "contribute to and extend the broad movement of citizen engagement in vital research on climate change and its consequences by making possible the contribution of student-collected data to scientists' understanding of local effects of climate change." The STSP was designed in collaboration with curriculum writers working at an independent STEM educational research and development organization in the United States. The curriculum writers brought knowledge of the relevant science and an "appropriate range of skills, attitudes, and cultural sensitivities" to facilitate the school-scientist partnership. Although curriculum writers were involved in this capacity, the design work focused on the goals, needs, and concerns of the scientists and school partners, who were the stakeholders in the present STSP.

The STSP intended to deepen students' understanding of the central concepts and practices in climate science, including the concepts of weather, precipitation, and temperature, and the practices of fieldwork techniques and analyses of longitudinal data sets. The curriculum consisted of two main components: an in-class unit and fieldwork. The in-class unit was of one week duration to help middle school students (of ages 12-13 years) investigate climate change as it manifested in the local environment. It was aligned with the science education frameworks in the U.S. stressing instruction in disciplinary core ideas, cross-cutting concepts, and practices (NRC, 2012). The in-class materials contained guides for teachers and students (see Results for more details).

The unit was also aligned with a standardized vegetation fieldwork component, in which students gathered data on leaf length and width and canopy cover on transects near their school grounds twice over a two-month period each year (ideally) – at first leaf opening, and at full leaf expansion (see excerpt of fieldwork protocol in Figure 5.2). Additionally, students measured height and diameter at breast height (DBH) of trees once a year. The vegetation measures had been established by the ecologists through previous collaboration with students to study migratory bird responses to climate change. In addition to engaging students in the present STSP with scientific practices, the vegetation data (as indirect indicator of insect availability) were intended to help the partner ecologists examine over the long term how ecosystem changes, including those in temperature and vegetation, influence bird behavior. As clarified in the curriculum materials, the data on bird biology and behavior collected by the scientific research institution over many decades indicated that migratory birds have changed their seasonal behavior with rising temperatures and are returning earlier. Other regional phenology data, such as frog calling and butterfly range shifts, also indicated that some organisms were responding to the warming climate. To understand better how other local species were changing in measurable ways, the ecologists predicted that trees and shrubs in the local region would respond by leafing out earlier (bud-break and full-expansion), and over time, were expected to grow at higher rates as measured by height and DBH. There were also supplementary fieldwork options involving less standardized data collection (e.g., maintaining a phenology calendar about birds, plants, and insects) to yield more short-term and thus more rewarding results in terms of climate change (Bopardikar, Bernstein, & McKenney, 2021; see Results for more details on a menu of fieldwork project options).

Fieldwork materials for students took the form of kits (containing micrometers and DBH measuring tape), written stepwise protocols, and print-based data record sheets created by the ecologists. For teachers, there were also short videos in which the ecologists demonstrated their methods and offered tips for locating suitable sites to gather standardized vegetation measurements. For less standardized fieldwork, there were briefs, background information, and criteria and tips for data collection and reporting to various phenology and scientific programs. Finally, there were webinars for teachers' professional development (PD). The in-class unit, fieldwork, and teacher PD webinars were intended to scale up to involve schools and scientist partners in different regions of the U.S.



Leaf Measures

Why you are measuring leaves:

We can look at weather data (collected by entities such as NOAA) to determine whether a year is warmer or cooler than average, but information on organisms' responses to climate change is much harder to come by. This is where you can help!

In much of the country, many plant species drop their leaves to avoid the harsh winter weather. When spring arrives, these species then grow leaves in a process we call leaf out. For understory species and small trees it is important to leaf out earlier than the trees in the forest canopy in order to take advantage of the early spring sunlight.

As you have learned through the <<curriculum>>, timing is an incredibly important aspect in natural systems. Leaf out timing can be influenced by several factors, including temperature. In warmer years, plants often leaf out sooner. By measuring leaves during leaf out **and** after the leaves are fully grown, we can determine how far along leaves were at a certain date. Over time, we can use the data to monitor trends in both leaf out dates and in growth rates over the course of the growing season.

What you will need:

-Measuring device capable of measuring to the nearest millimeter (an ordinary ruler with tape over the "inches" side will suffice)

-Data Sheets (found on the <<curriculum website page>>)

How you will do it:

You will be selecting trees, shrubs or herbs with measurable leaves in the general area of your study site. Be sure to select species that:

-are native species
-are numerous in your study site
-replace their leaves each spring
-do not have compound leaves (such as Ash, Sumac or Locust trees)

-Select six independent plants or trees of the same species. Try to select plants that will not be altered/removed over the course of years.
-Label these plants in a permanent manner. You will need to measure leaves on these plants twice a year for the foreseeable future, so we would suggest using metal tree tags, which we can supply you with. If available, a GPS can be used to note the specific locations, or students can create a diagram of your study site.
-For each plant, randomly select five leaves. We suggest having the measurer close their eyes and feel for one leaf at a time. The person recording data can make sure no leaves are measured twice.
-Measure and record length to the nearest millimeter. Do not include the petiole/ leaf stalk (see Figure 1)
-Measure and record width to the nearest millimeter. Width should be measured at the widest part of the leaf.
-Once the plants have fully leafed-out, return to the same plants and repeat steps 3-5

Figure 5.2: Fieldwork protocol for leaf measurement.

5.2.2 *Evidence of STSP impact*

We deem this a successful design case, based on project documentation showing a positive impact on student learning. Student responses on written pre-and-post assessments created by the designers showed significant improvements in students' understanding of weather versus climate; impact of seasons on plant and animal life activities; and species' response to climate warming (see Table 5.1). All of the questions on the pre-post assessments required constructed responses. To assess the responses, initially during the STSP design work, a set of open codes was developed, applied, and refined by the designers through negotiation among members of the design team, with an inter-coder agreement greater than 80%. The codes identified: (i) incomplete or unintelligible answers, and (ii) incorrect answers, in contrast to answers that were (iii) brief but at least partly correct, (iv) correct but incomplete, or (v) correct and full. For the purposes of the quantitative analysis, the designers collapsed all five conditions as described above into two categories: i and ii, vs a combination of iii, iv, and v. The revised pre-post questions and analytic codes were then used to assess students' understanding during subsequent implementations of the STSP, with two members of the design team coding all responses and resolving differences in codes. Furthermore, feedback from teachers revealed the fieldwork to be of value and the in-class unit to be usable and well-aligned with their curricular needs.

Table 5.1: Changes in students' understanding of specific topics.

Topic	**Percentage of students providing satisfactory, complete, and/or accurate responses on the pre-assessment**	**Percentage of students providing satisfactory, complete, and/or accurate responses on the post-assessment**	**Z score and p-value**[11]
Distinguishing weather from climate	~ 42%	~ 72%	-5.253, p < .0001
Impact of seasons on plant and animal life activities	~ 63%	~79%	-2.336, p = .02
Species' responses to climate warming	~ 17%	~ 28%	-3.467, p = .001

5.2.3 *Participants, procedures, and data sources*

Four designers participated in this case study. Two of the designers were ecologists from the scientific research institution mentioned previously. While practicing scientists, they had facilitated activities for environmental education previously. As such, they were both designers of and stakeholders in the present STSP. The other two designers were curriculum writers from the educational research organization; they had training in ecology and prior experience with science curriculum design. One of them served as project leader. All participants signed informed consent documents prior to the start of the study, which included granting the researchers access to relevant dialogue, to design documents, and to data gathered by the

---

[11] The Z-score was calculated based on a sample of 73 students, with Wilcoxon Signed Ranks test based on negative ranks.

designers about student learning and teacher implementation[12]. However, whereas the designers provided various data for the study, they did not serve as authors of this paper. Furthermore, whereas the authors gathered data for this study from the designers, they were not directly involved in designing for the STSP, nor were they stakeholders in this partnership. As elaborated below, the first author led the data collection, analysis, and reporting for the study, while the second and third authors played a supportive role by providing feedback to guide these efforts.

The study took place over a three-year period, during which the first author served as a participant-observer for approximately half of that time and was 'immersed' in the regular design work conducted by the participants (Emerson, Fretz, & Shaw, 1995). During this time, multiple overlapping methods were used in conjunction to enable prolonged engagement with and persistent observation of the design work and to yield dependable findings (Guba, 1981). Casual direct observations were made (Yin, 2014), interviews were conducted, and documents were gathered from the middle of the first year, as the designers were preparing for the first cycle of testing to nearly the end of the second year, as the designers were conducting the second cycle of testing. After the observational period ended, document and interview data continued to be collected and analyzed.

Three sources were used to triangulate the data and generate credible and confirmable results (Guba, 1981; Yin, 2014). First, researchers kept observational notes of the design team's weekly meetings and enactment of standardized vegetation fieldwork at a local school site. The notes were generally drafted immediately upon observing those events to record the complexity of designer reasoning and action (Emerson et al., 1995). Second, designer-generated documentation was collected and analyzed. This included planning documents; email communication; drafts of materials for the in-class unit, fieldwork, and teacher professional development; project grant proposal; written pre-and- post assessments of students' understanding; and teacher surveys. Finally, the project leader was interviewed three times throughout the project and each of the other participants was interviewed twice, for a total of nine interviews. The interviews were semi-structured and aimed to inquire more deeply into designer thinking and methods behind curriculum supports created to implement the STSP. Sample questions were: *How important is this [boundary crossing process] to your STSP model and why? In helping other scientists and schools to [engage in the boundary crossing process], what factors, requirements, or constraints did you take into account while developing these materials? How did you arrive at these insights/decisions?* The interviews were conducted individually and lasted 80-110 minutes. Together, the three data sources contributed to understanding evolving designer considerations about stakeholder needs, curriculum supports, and design methods.

5.2.4 *Data analysis*

The data were analyzed in two phases. During the observational period of the study, the data from fieldnotes and documents were analyzed to understand designer thinking and activities behind various elements of the curriculum created for the

---

[12] This research was approved by the Institutional Review Board at TERC.

STSP. Grounded in emergent interpretations of the data, this analysis resulted in interim reports describing designer thinking and activity to help the designers to take stock of their work. The first author prepared drafts of the reports, which were discussed and iteratively revised with the co-authors until there was consensus. Member checks (Guba, 1981) were conducted with the participants to verify and revise the reports as appropriate. The interview transcripts were analyzed initially by the first author, then reviewed independently by the second author to verify and extend the interpretations. After the three-year period, guided by the codes described in Table 5.2, all data were reviewed by the first author to confirm and elaborate a full set of findings about stakeholder needs, curriculum supports, and designer methods to create those supports. The a priori codes were based on the three dimensions of the theoretical framework. They were applied deductively (Miles & Huberman, 1994), and the code definitions were refined through feedback from the co-authors and the project leader when discussing sample excerpts. Thereafter, a draft case study report was discussed with the authoring team, further refinements to the coded data were made until 100% consensus was reached, and finalized after a final member check with the project leader (Yin, 2014).

Table 5.2: Coding scheme to analyze designer work in creating STSPs.

Code	Definition	Sample Excerpt
		Understanding Stakeholders (Boundary Crossing Processes)
Othering	Stakeholders understand different practices in relation to one another.	[Excerpt from designer interview]: Teachers, and through them the students, need to understand more about the science, the meaning of it from the scientific point of view, so they can fit it into their whole curricular purpose. And it's not evident to a working scientist that in order to make sure that the data are collected reliably, the teacher and through them the students need to have a good feel for why these data are being collected, what is gained or lost by the quality of the data.
Communicative Connection	Stakeholders perform distributed work through routines and procedures.	[Excerpt from designer interview]: You do have to provide more information for teachers when you are [designing options for fieldwork], and you have to be prepared to provide more protocols and refer them. And you can't just refer to – look at this website, this is how you study insect abundance. You have to very precisely say, lay out the white sheet. Hit the tree. Count the insects down below. Contribute it to the following database.
Joint Work	Stakeholders engage in continuous dialogue and negotiation of meaning.	[Excerpt from an annual progress report to the grant funding agency]: In many cases the teachers didn't really know how to conduct field work, and weren't comfortable or knowledgeable about the natural history of their area. The presence of enthusiastic and knowledgeable naturalists as represented by [partner ecologists] meant that the routine of field work was enriched or enlivened by stories, spontaneous comments about other features noted, and interaction with the naturalist "habits of mind" that make field work stimulating and engaging. Moreover, [partner ecologists] provide a warrant for the authentic value of the field work, which was exciting and motivating for students and teachers alike.
		Curriculum Supports
Participation	Interactions, roles, and responsibilities envisioned for stakeholders.	[Excerpt from newsletter to teachers]: This year, you will be the ones leading these field sessions, so it is imperative that you understand the techniques and rationale for the data you are collecting. The combination of the protocols, instructional videos, and recorded webinars will provide you with the information you need to master the techniques and relate them to the curriculum.

Tasks	Learning activities envisioned for stakeholders' participation.	[Excerpt from designer notes in planning documents to envision fieldwork projects]: Original vegetation sampling both during early spring leaf out and later once leaves are fully grown. Schools must set up and/or maintain one or more transects in a green space near the school. These transects serve as reference points for annual fieldwork.
Materials	Digital and/or print-based resources to help stakeholders engage with the envisioned tasks.	[Questions in the in-class teacher guide to facilitate a whole-class discussion]: Which species is most vulnerable to ecological mismatch, and why? How could we use bird data or other data as "bio-indicators" of what's happening to Earth's climate?
	Design Methods	
Analysis	Designer work to uncover stakeholder needs and to derive initial design requirements and specifications for creating curriculum supports	[Excerpt from survey administered to teachers about curriculum and fieldwork implementation]: Question: Were there aspects of the program you would have wanted more training or support on? Responses: orientation to the curriculum, field techniques, data analysis, connecting curriculum to field activities.
Development	Designer work to determine content and sequence of instructional activities and to craft curriculum materials for supporting the envisioned participation and tasks	[Excerpt of design principles to develop fieldwork projects involving different "effort-levels," as described in an annual progress report to the grant funding agency]: (i) The field activities at each "effort level" will produce data of scientific interest — to the students as well as the scientists, and suitable for contribution to data sets being collected aggregated by other projects (e.g. the National Phenology Network, Audubon, or regional phenology research). (ii) The activities at each effort level should be accompanied by supportive materials for student and teacher linking the content and the practices necessary for the research component to the school curriculum and NGSS.
Evaluation	Designer work to test and guide revisions to curriculum prototypes	[Excerpt from designer notes about student-generated data from the standardized vegetation fieldwork]: Although they were provided with seemingly ample tools, no school was successful in collecting a complete set of pre-leaf-out data. No school got out a second time to collect post-leaf-out data. These findings suggest a major shift in our data-collection requirements/methodologies is necessary if we anticipate further program expansion without a serious drop-off in data quality.

5.3 Results

This section takes designer understanding of stakeholders as the leading organizing principle and portrays how insights concerning the boundary crossing processes of othering, communicative connections, and joint work emerged over time. Curriculum supports are described in relation to each boundary crossing process, along with the design methods through which the supports were created to aid stakeholders' engagement in those processes. The main findings are previewed in Table 5.3 as an advanced organizer.

Table 5.3: Main findings about designer attention to stakeholder needs, curriculum supports, and design methods.

	Boundary Crossing Processes		
Understanding Stakeholders	Othering: Clarify standards-aligned science content for student learning, nature of partner scientists' research	Establishing communicative connection: Enable suitable data collection, exchange of fieldwork information between schools and their partner scientists	Continuous joint work: Regular interactions among partners, with substantial dialogue and negotiation of meaning around shared goals
Curriculum Supports	Participation: Students would participate in teacher-facilitated discussions; scientists would motivate fieldwork Tasks: Individual assignments; whole-class, small group discussions; teachers would guide student tasks through questions and specific directions; scientists would communicate fieldwork rationales and theoretical connections through curriculum materials. Materials: Regionally	Participation: Teachers would facilitate fieldwork projects connected to scientific programs; scientists would provide guidance for contributing student-gathered data to suitable scientific programs Tasks: Students would gather data on specific species, contribute data to class discussions, local partner scientists' research, national databases; teachers would guide students through questions and stepwise directions; scientists would identify ecological programs, provide materials for students' investigations.	Participation: Teachers and scientists would engage in mutual communication towards shared educational and scientific goals. Tasks: Teachers would participate in PD webinars, provide feedback on in-class unit, fieldwork; scientists would assist through in-person, electronic communication Materials: Newsletters; online webinars (recordings)

	customized curriculum presents relevant readings, authentic data sets for in-class unit; Teacher Guide clarifies learning goals, questions, desired student responses, fieldwork purposes	Materials: Hands-on kits; menu of fieldwork options; written protocols; data sheets; video tutorials; briefs, background information; stepwise guidelines for analyses of student-gathered data	
Design Phases	Analysis: Gathered teacher feedback on interest in enacting data analytic tasks Development: For customization, reviewed information on relevant regional ecosystems; gathered input on locally relevant data sets from scientists	Evaluation: Early pilot trials in local schools revealed standardized fieldwork challenges Development: Reconceptualized scientific research program behind fieldwork; surveyed citizen science programs, protocols; drafted fieldwork options; refined drafts based on ecologists' input	Evaluation: Observations, teacher surveys from pilot trials revealed benefits of scientist presence, challenges in curriculum enactment, need for supplementary fieldwork, data analysis activities Development: Gathered teacher recommendations for webinar content

5.3.1 *Othering: Identifying practices of schooling and climate science research suitable for classroom enactment*

5.3.1.1 Understanding stakeholders

Though designers used other terms to describe it, their work clearly supported STSP stakeholders to engage in othering. For example, interviews, design documents, and observations of designer team meetings revealed that to help school practitioners consider disciplinary practices alongside science education standards, the designers attended to teachers' difficulties with enacting data analytic activities in relation to fundamental climate science concepts. While the current science education standards emphasized teaching climate change, teachers lacked adequate supports to enact those standards. This was especially so with the central scientific practice of data analysis. As a curriculum writer explained during interviews, previous in-person discussions with local teacher participants (during *the analysis phase*, prior to commencing this study) had indeed indicated interest in enacting data analytic tasks to facilitate the integration of science and mathematics in their classrooms. However, whereas teachers and students might participate in data collection, they typically resisted sensemaking of the data.

5.3.1.2 Curriculum supports

Participation. During team meetings, the designers thus formulated a vision for teacher and student participation, centered on teacher-facilitated whole-class and small-group discussions around authentic data sets. The discussions aimed to help students understand patterns in long-term data sets in relation to relevant climate science concepts and to understand the epistemology of science – "how we know what we know." Scientists were expected to motivate students and teachers to conduct fieldwork, for example, by explaining the relationship between fieldwork techniques (e.g., measuring leaf-out to document vegetation changes) and larger ecology concepts in climate science theory related to their research. In formulating this vision, the designers considered the challenges of scientists in communicating their research rationales and data requirements in engaging and accessible ways to middle school students to enable them to contribute reliable scientific data. As a curriculum writer noted during interviews, it was important to help teachers:

> *…understand more about the science, the meaning of it from a scientific point of view, so they can fit it into their whole curricular purpose. And so, the science has to be brought towards them, so they can see how for those concerns. And the curriculum developer also needs to think about how much of the science might be unfamiliar to the teacher. So there's translation from the science side in that direction… it's not evident to a working scientist that in order to make sure that the data are collected well, collected reliably, the teacher and through them the students need to have a good feel for why these data are being collected, what is gained or lost by the quality of the data. For the scientist, that's obvious because you don't suggest data collection unless you've got a purpose… so, they need to understand and be patient with the curriculum developer to unpack it in ways that reach the right grade level.*

Tasks. To bring this designer vision to life, as drafted in the teacher and student guides early in the STSP, in-class *tasks* for students included completing individual assignments and engaging in whole-group and small-group discussions. These tasks were centered on readings and authentic data sets involving both student-gathered vegetation data and longitudinal bird data obtained from the partner ecologists' research, mainly pertaining to the ecology of northeastern United States region. The discussions also addressed standardized vegetation fieldwork rationales and techniques prior to conducting the fieldwork. The tasks for teachers were to raise specific questions and provide specific directions to guide the flow of these instructional activities in the classroom. Whereas these tasks were to be enacted by students and teachers in the classroom, the task for scientists was to support classroom enactment by clarifying through curriculum materials the scientific rationales behind the fieldwork and its basis in broader climate science theory.

Materials. The teacher guide for the in-class unit included questions and desired student responses around readings and data sets related to climate science concepts and educative notes about students' conceptions regarding climate change. There were also tips for discussing the rationales for the fieldwork techniques and the hypotheses behind the standardized vegetation fieldwork as it pertained to the partner ecologists' ongoing research. Thus, through the written materials designed to enact the vision for in-class participation and tasks, the designers hoped to clarify (and help stakeholders understand) standards-aligned science content that framed classroom instruction and the fieldwork rationales and techniques that framed ecological practice of scientists, delineating how these related to one another. The findings presented below on design phases show how the in-class curriculum was revised later by the designers to customize the content to different geographic regions, thereby geared towards supporting school partners and scientists with respect to this particular boundary crossing process.

5.3.1.3 Design phases

Development. The original curriculum was designed for schools in the northeastern region of the U.S. and aligned with bird data gathered by the partner ecologists. As described earlier, it situated the standardized vegetation fieldwork within research on climate science to help school partners understand how climate science theory (as conveyed through concepts emphasized in curriculum frameworks in the United States) related to the study of specific aspects of biology conducted by partner scientists in their local region. To extend the STSP later to a geographical region on the west coast of the U.S., the designers sought to adapt the in-class curricular content to continue supporting new school partners to understand scientific practices, especially collection and analyses of longitudinal data sets as embodied in the work of local partner scientists, in light of the science curriculum frameworks. In so doing, adaptations to readings and associated data sets about bird species were crucial. To that end, and as envisioned originally in the grant proposal and explained later during interviews, a place-based learning approach required revisions to make the curriculum relevant to schools and scientific research in that region and also to maintain the motivational value of associating with local environments (and local organisms) to foster student engagement and learning. Through the local environment, the designers hoped to provide students with both an empirical basis to learn about climate change based on what students could see happening around them and an affective connection to local organisms so they would engage more deeply with the content. A curriculum writer reasoned thus about customizing the curricular content to the local ecological context:

> *Our conviction [is] that the science of climate change is going to be the most accessible, and possibly the most actionable, for people if they see it happening locally. So that's been the focus of most of our climate change work. So, we developed the curriculum to have the most impact for people in [more specific region in northeastern U.S.]. And that was nice because it connected best with the data set from [the partner scientific research institution]. So, what that meant was that if somebody else wanted to try out this general approach, the place-based element of it required revision and customization.*

To customize the curriculum, the designers began considering possible substitutions with respect to longitudinal data and stories to depict in the curriculum. A curriculum writer reviewed the original curricular content to identify specific data sets and readings about bird species related to the northeastern U.S. to be replaced with content relevant to the west coast. Further, information on ecosystems on the west coast was reviewed to understand better the climatic differences compared to the northeastern U.S. An ecologist consulted with science educators at research stations on the west coast about migration timing of common bird species in response to climate change. As noted in designers' email communication and drafts of the revised curriculum materials, new longitudinal data sets and stories reflecting local conditions were substituted into the in-class unit. In fact, during interviews, this is how an ecologist emphasized the importance of seeking input from local scientists to customize the curriculum for geographic relevance:

> *When we go to an area that is different, we have to find out from the local scientists which would be good species to look at and feature, ideally something the students know. So we worked with the scientist educators in [a scientific research institution on the west coast] to find out some migratory species that were coming a short distance and were coming back earlier because of climate change. And as with [birds studied at their own scientific research institution], some very long distance migrants do not detect climate change, and therefore are not coming back earlier. And we contrasted one species that does that there and another species that is reacting to climate change. And that uses local data. And there's perhaps even a good chance of when the students go out and measure vegetation in the field there, they may see those birds, and the teachers will say to them, there's the bird that's in your curriculum.*

5.3.2 Communicative connection: coordinating fieldwork

5.3.2.1 Understanding stakeholders

Designer work supported STSP stakeholders to *establish communicative connection* to coordinate their fieldwork through suitable data collection and exchange of relevant information. During interviews, the designers explained that they viewed fieldwork in STSPs as breaking barriers between science and the general public, empowering students to understand what was involved in collecting data and generating findings, and to recognize their role in contributing to climate science knowledge building. This was deemed critical to help students understand real-world effects and to nurture their personal interest in and concern for the real world through first-hand experiences in local, personally meaningful surroundings. An ecologist described the importance of fieldwork thus:

> *Everyone, I think, is aware, especially in conservation biology and field biology, that fewer and fewer of the students even up to college level that you get … have had the experience of going out in the field. So, we thought an important aspect is really to put people back in touch with the real biology that is going on all around us. And unless everyone understands that these are real world effects, if they haven't experienced the real world, why would they care? So, a very important part of [the STSP] was to get students out of the classroom and get them into the field, even if it's only for two or three afternoons during the whole*

> *year, just for a period when they can collect some data, learn how to do this. And that gives them a personal interest in what's going on.*

5.3.2.2 Curriculum supports

Participation. The vision for participation, as formulated in the grant proposal and as enacted subsequently, emphasized students' involvement in fieldwork that was framed (and motivated) by research projects introduced by partner scientists and other broader research programs. The designers also stressed that teachers would facilitate the fieldwork, and scientists would provide guidance on contributing student-gathered data towards appropriate scientific programs.

Tasks. During team meetings and in design documents there was evident a refined vision that students would collect and discuss observational and/or measurement data related to vegetation, birds, and insects near their school grounds. The designers also intended for students to contribute those data to research conducted by partner scientists and/or other national citizen science databases. The tasks for teachers included guiding students on the field and in class through questions and stepwise directions for planning and conducting different ecological investigations. The tasks for scientists were to identify suitable ecological programs for which student investigations could contribute meaningful data and to create or adapt as required specific protocols and materials to support school partners in conducting the investigations.

Materials. For the standardized vegetation fieldwork, early in the STSP, the designers provided school partners with hands-on kits, written protocols, data sheets for recording observations and measurements, and video tutorials demonstrating the ecologists' techniques to assist with collecting various vegetation data. Additionally, for supplementary fieldwork envisioned later in the STSP, there were science briefs and other background information. Finally, there were tips to help students analyze the data and report the findings to suitable scientific programs (see also the section on Research Approach for details about the fieldwork). Thus, through the written materials designed to enact the vision for fieldwork participation and tasks, the designers intended to provide school partners and scientists with effective means and procedures to cooperate around field activities and to exchange relevant information (e.g., research questions, data collection guidelines, data sets, etc.), thereby coordinating the flow of data across different sites. These materials have been reported in more detail in our previously published work (Bopardikar et al., 2021). The findings on design phases presented below show particularly how curriculum supports for supplementary fieldwork geared towards this boundary crossing process were generated by the designers.

5.3.2.3 Design phases

Evaluation. The designers observed pilot implementations of the standardized fieldwork to evaluate the extent to which teachers were comfortable with the content, prepared to lead the tasks, made any modifications, and faced logistical issues including time constraints. They also noted the extent to which students were engaged and seemed to understand the content. Additionally, the ecologists evaluated the extent to which relevant, accurate, and complete vegetation measurements were submitted by the school partners. They noted that school partners had difficulty in following the standardized protocols and data sheets, and that limited time was available to complete the standardized fieldwork, in part due to conflicts in the timing of spring vegetation development and standardized assessment schedules in schools. These challenges resulted in the schools' contributing vegetation data that were incomplete, contained errors, and had limited utility.

Development. In subsequent team meetings for redesigning the fieldwork, therefore, designers considered tailoring the fieldwork by providing a broad framework adaptable to the purposes, preferences, requirements, and constraints of schools and their partner science organizations in different regions to scale up the STSP. The result manifested in a menu of project options to help teachers plan fieldwork that would be both useful for science and within the means of the school partners. The options on the menu represented different “effort levels” according to the complexity of set up; estimated time required; number of variables under study; amount of data; extent of data management; time for teacher professional development; and the number of required class discussions. The low effort-level projects involved simpler protocols for feasibility from the teachers’ point of view and reliability from the scientists’ point of view. This was important to help students generate data that would be of value and avoid simply going through the motions of learning techniques. The more ambitious projects involved stricter protocols for reporting to different ecology programs. This was important to highlight the scientific value of the fieldwork and to enable students to not only explore their own data sets but also bigger data sets collected nationally. As an ecologist explained during interviews, although precise implementation, standardized data, and the scientific method were important to scientists, the emphasis of this STSP was on:

> *This field now of citizen science where people are contributing parts to a database. We realized if we can make this more relevant in terms of contributing not just to what [present scientific research institution] would do and what [they] would like, but to national databases that can be used by any scientists who are studying climate change.*

Furthermore, a curriculum writer recalled during interviews that the projects could be implemented in a variety of spaces available to students, such as in their local surroundings or on transects set up specifically for the fieldwork. This was important to reduce dependence on proximity to natural environments, which was pertinent especially to urban areas. Additionally, the menu indicated alignment of the content with the standards in science curriculum frameworks in the United States to highlight the pedagogical value of the science embodied in the fieldwork projects.

Finally, given the interdisciplinary nature of the subject and informed by teacher feedback, designers stressed modularity in fieldwork to help teachers incorporate the projects in different grades or different content areas (e.g., earth science or life science). This was important because the climate science education standards were addressed in varied ways in different schools. The modular design, however, also meant thinking about how the fieldwork options would build towards a coherent structure to contribute towards both science education and scientific research. During interviews, a curriculum writer articulated the challenge thus:

> *If you snap them all together, it should be a unit, but if you take it apart, each sub-unit should be able to stand on its own. And yet, call out to the others at some point. If we allow more pluralism in regard to field activities, then the [fieldwork] options have to make sense from the point of view of the scientific research program. So that meant clarifying the scientific research program to the point that the pieces that we offered to the schools actually could project onto this larger thing.*

Guided by these specifications and rationales, input from the ecologists, and similar ideas in regional ecology research, the curriculum writers first reconceptualized the STSP's original scientific research program into a broader program on emerging regional cross-trophic level impacts of climate change, identifying hypotheses and species to address in the program. The revised program focused on a systemic context for climate change-related research, with connections among plants, insects, and bird arrival times and the ripple effects of temperature and precipitation changes on these organisms. This step was critical to explicate the relevance of students' fieldwork to citizen science programs with strong scientific rationales and clear questions to answer. There was flexibility in choosing species to contribute a variety of rigorous long-term data, giving students and teachers opportunities to engage with science that was not only meaningful but also pedagogically valuable. For example, they could study a particular warbler, its favorite caterpillar, and the caterpillar's favorite food plant, or worm-eating warblers in general, or fruit-eating birds and the pests on the fruit.

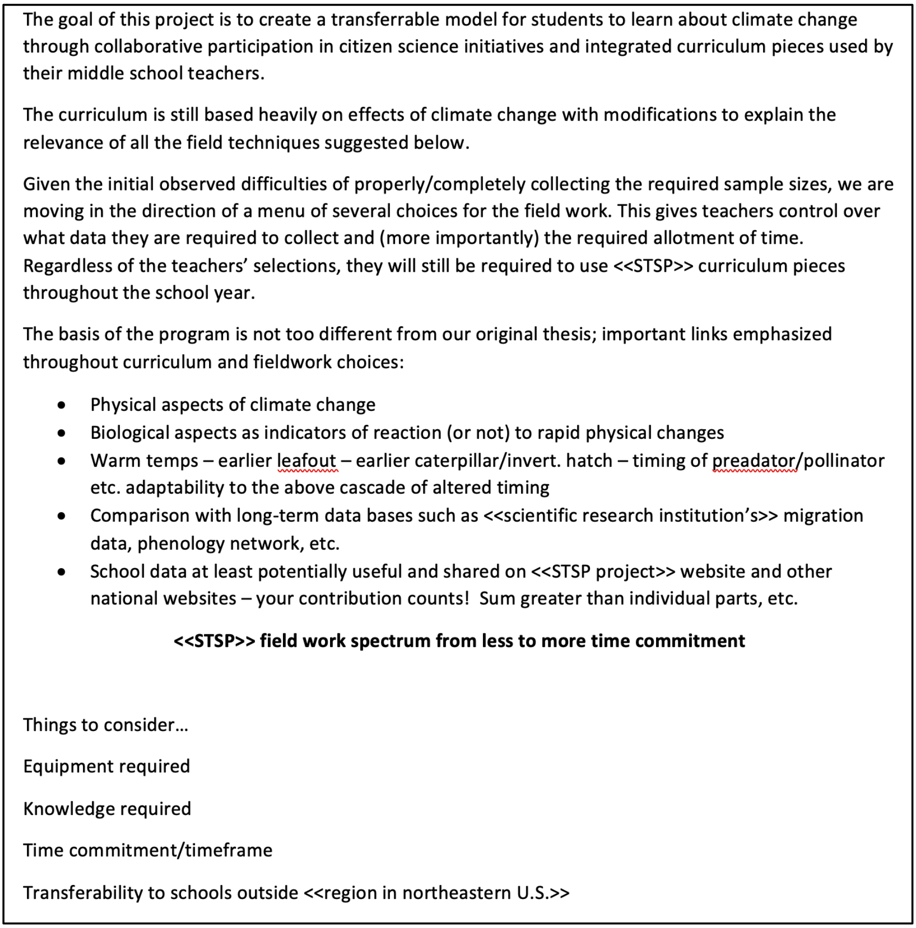
Based on the scientific research program, several design principles emerged to guide the creation of different effort-level projects, as explained in a progress report to the funding agency. For example, one principle stated that at each "effort level", the field activities "will produce data of scientific interest — to the students as well as the scientists, and suitable for contribution to data sets being aggregated by other projects (e.g. the National Phenology Network, Audubon, or regional phenology research)." Another principle stated that effort-level activities "will be coordinated with each other, so that they form a mutually supportive suite of activities of educational and scientific interest."

Following this reconceptualization, the designers took various measures to develop the fieldwork projects. The interviews and planning documents indicated that they surveyed existing phenology and citizen science programs, stressing projects involving stepwise protocols to reduce student error in measurement. The longitudinal nature of citizen science databases was an important consideration, as recalled by an ecologist elaborated during the interviews:

> *The first thing you do is you sort of cast around amongst all of your colleagues and try to find what databases are there, not just in my particular field of*

> *information, which might be birds in my case, but what is there on plant phenology and what is there on insect abundance. And so, you have to find some databases that are, first of all, probably going to continue. And so, if we're talking about - wouldn't it be nice if we can look back ten years from now and see that data contributed, you have to know that the database is going to be there ten years from now. And then you have to look at the protocols, which… are designed for citizen scientists. Students are citizens. Students are very capable of doing more than you would think. And that's part of the learning. So, you have to adapt it to whatever would be appropriate for middle school.*

The ecologists drafted a preliminary menu of fieldwork projects, specifying the overall links to key science content and citizen science contributions. The initial menu provided brief descriptions of the projects and proposed criteria to categorize the projects along a spectrum, namely time commitment, pre-requisite knowledge and equipment, and transferability to schools outside their immediate region (see



The goal of this project is to create a transferrable model for students to learn about climate change through collaborative participation in citizen science initiatives and integrated curriculum pieces used by their middle school teachers.

The curriculum is still based heavily on effects of climate change with modifications to explain the relevance of all the field techniques suggested below.

Given the initial observed difficulties of properly/completely collecting the required sample sizes, we are moving in the direction of a menu of several choices for the field work. This gives teachers control over what data they are required to collect and (more importantly) the required allotment of time. Regardless of the teachers' selections, they will still be required to use <<STSP>> curriculum pieces throughout the school year.

The basis of the program is not too different from our original thesis; important links emphasized throughout curriculum and fieldwork choices:

- Physical aspects of climate change
- Biological aspects as indicators of reaction (or not) to rapid physical changes
- Warm temps – earlier leafout – earlier caterpillar/invert. hatch – timing of preadator/pollinator etc. adaptability to the above cascade of altered timing
- Comparison with long-term data bases such as <<scientific research institution's>> migration data, phenology network, etc.
- School data at least potentially useful and shared on <<STSP project>> website and other national websites – your contribution counts! Sum greater than individual parts, etc.

<<STSP>> field work spectrum from less to more time commitment

Things to consider…

Equipment required

Knowledge required

Time commitment/timeframe

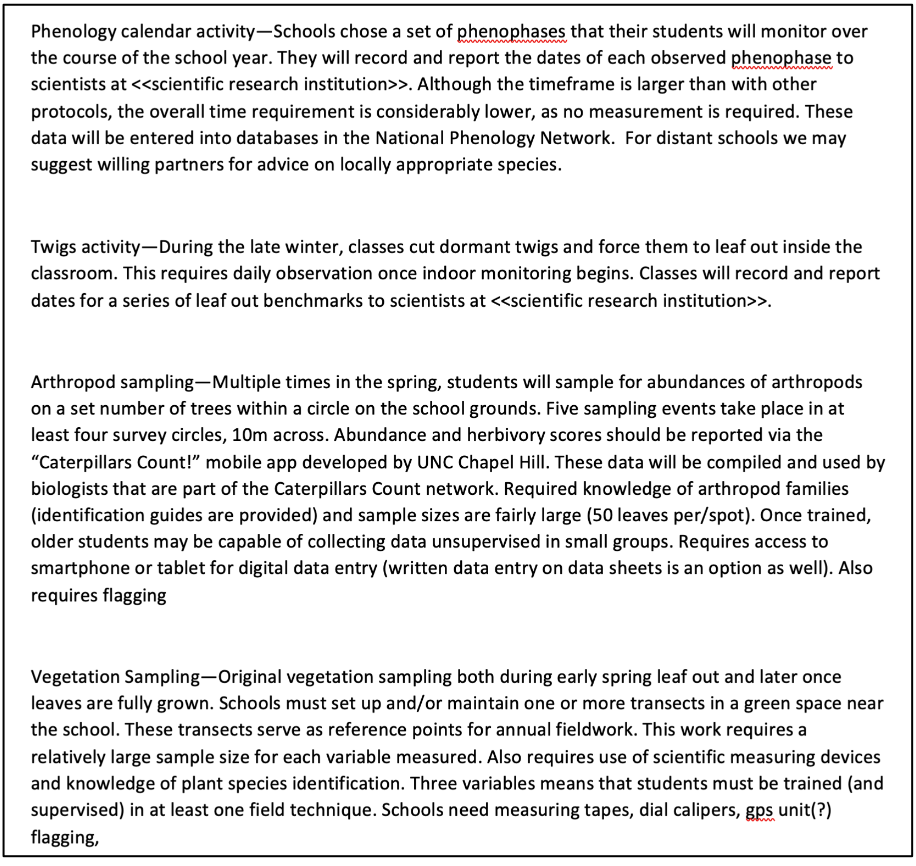
Transferability to schools outside <<region in northeastern U.S.>>

Figure 5.3: Project document showing preliminary designer ideas for fieldwork menu.

Figures 5.3 and 5.4 for project documentation showing preliminary designer ideas about fieldwork projects).

Accordingly, the curriculum writers elaborated drafts of fieldwork projects involving different effort levels, and these were informed by the nature of help sought by the partner teachers during previous evaluation of the STSP. For each project, the curriculum writers formed conjectures about its purpose and value to other scientific research programs; estimated time requirement; and protocols. Finally, they refined drafts of background materials for the projects based on clarification and elaboration of science content from the ecologists. During interviews, this is how a curriculum writer described their considerations behind the fieldwork menu:

> *It's got to be meaningful science, but it's got to be pedagogically valuable science. It's got to be useful data, but the data collection has to be within the scope of means of the teacher that's doing it. So, [another curriculum writer] started putting out versions [to] give the teachers a sense [of] like, how demanding is this going to be? So, low, medium, and high effort. And there are*



Phenology calendar activity—Schools chose a set of phenophases that their students will monitor over the course of the school year. They will record and report the dates of each observed phenophase to scientists at <<scientific research institution>>. Although the timeframe is larger than with other protocols, the overall time requirement is considerably lower, as no measurement is required. These data will be entered into databases in the National Phenology Network. For distant schools we may suggest willing partners for advice on locally appropriate species.

Twigs activity—During the late winter, classes cut dormant twigs and force them to leaf out inside the classroom. This requires daily observation once indoor monitoring begins. Classes will record and report dates for a series of leaf out benchmarks to scientists at <<scientific research institution>>.

Arthropod sampling—Multiple times in the spring, students will sample for abundances of arthropods on a set number of trees within a circle on the school grounds. Five sampling events take place in at least four survey circles, 10m across. Abundance and herbivory scores should be reported via the "Caterpillars Count!" mobile app developed by UNC Chapel Hill. These data will be compiled and used by biologists that are part of the Caterpillars Count network. Required knowledge of arthropod families (identification guides are provided) and sample sizes are fairly large (50 leaves per/spot). Once trained, older students may be capable of collecting data unsupervised in small groups. Requires access to smartphone or tablet for digital data entry (written data entry on data sheets is an option as well). Also requires flagging

Vegetation Sampling—Original vegetation sampling both during early spring leaf out and later once leaves are fully grown. Schools must set up and/or maintain one or more transects in a green space near the school. These transects serve as reference points for annual fieldwork. This work requires a relatively large sample size for each variable measured. Also requires use of scientific measuring devices and knowledge of plant species identification. Three variables means that students must be trained (and supervised) in at least one field technique. Schools need measuring tapes, dial calipers, gps unit(?) flagging,

Figure 5.4: Project document showing preliminary designer ideas for fieldwork menu.

> *some cases where the same thing could be done with low effort, it would be valuable to a certain extent, or high effort, but then what value? For each one, I've tried to identify what would be the purpose. So, what's the activity? How much time would it take? What's the protocol? Who cares about the data? And the more targets, the better. To give, from the students' point of view, a way for the data to matter. From the teacher's point of view, the data matter, and they can think about what the learning is, and so, they can look at documentation, the student materials. And is there background knowledge that needs to be conveyed? And so then, there has to be a link to our curriculum. And the final thing was that we keep saying that all these data could be valuable in various ways for learning and exploration. And it seems like there's so much of this going on across the country that in almost every case, there should be a way to say that we can link this to the National Phenology Network, Nature's Notebook.*

5.3.3 *Joint work: transforming institutional practices*

5.3.3.1 Understanding stakeholders

Designer work supported STSP stakeholders to engage in *continuous joint work* via regular interactions around shared goals of the partnership. These interactions were conceptualized through a metaphor of "schools as satellite field stations," explained by the curriculum writers during interviews and in planning documents as a structure in which students and teachers would commit to "apprentice to research scientists by conducting a core set of data collection activities" linked to the research station's long-term study. Additionally, students and teachers would create their own research projects or join existing citizen science projects. For the scientists, the metaphor was expected to "reify [their] responsibility for good communication," providing a clear basis to commit their time to the STSP. The designers thus hoped to foster mutual accountability because "there was a common purpose and a certain sense of give and get" in the STSP.

5.3.3.2 Curriculum supports

Participation. To realize this metaphor, the designers envisioned teacher and scientist participation in dialogue and negotiation of meaning to help them make adjustments in their respective work and attain fruitful outcomes for both science education and scientific research. The adjustments for teachers, for example, involved incorporating target climate science content (in the form of the project's in-class unit) and fieldwork practices into their existing science curriculum, while those for the scientists involved extending fieldwork and demonstrating their research methods in different formats to accommodate diverse student and teacher needs.

Tasks. To facilitate the joint work, as envisioned in the grant proposal and implemented subsequently, the tasks for teachers centered on attending professional development meetings and providing feedback on the content and implementation of the in-class unit and fieldwork. The tasks for scientists focused on assisting the fieldwork in-person and through electronic communication and providing tips and clarifications about the research agenda. The curriculum writers explained during interviews that the tasks were intended to make the science more familiar and understandable to students and teachers, who may have limited access to scientists.

The in-person assistance from scientists would enable the school partners to see "naturalists in action", which would be both an affective sensory experience and a stimulating conceptual one. In the following excerpt, this is how a curriculum writer articulated the "educative power of personal contact" between scientists and school partners:

> *One of the things that most teachers can't do, and that students almost never see, and that requires a little time, and there's a certain leisure, is seeing a naturalist in action, where trudging to your field site allows you to encounter other organisms, other habitats. You're seeing potential questions and physical juxtapositions. It's both an affective sort of sensory experience and a deeply conceptual one… And if you're doing it with a bunch of students, and you build the relationship enough, they're not going to be in awe of you. They're going to be asking you questions.*

The personal assistance from scientists was expected to provide various benefits to students' engagement and learning of concepts and practices. The following excerpt from the grant proposal also portrays some of the envisaged benefits, inspired by the lead ecologist's personal presence on the field during prior work involving middle school students in gathering vegetation data to "bring science research closer to the classroom":

> *The [present scientific research institution's] ecologists, especially [the lead ecologist], played several critical roles. They [i] provided personal stories and engaged the students personally, [ii] were a key source of science content, [iii] perhaps most important, articulated the driving research questions behind the [scientific research institution's] research program and its context within climate change research, and [iv] provided instruction in science practices designed to further the research program, instructing students in transect layout methods, helped with data collection, and discussed and analyzed findings.*

Additionally, during interviews, an ecologist elaborated that interactions with scientists would "add weight to what [school partners] were doing" and help them see how gathering specific measurements was meaningful for scientific research. Indeed, surveys administered to teachers after the pilot evaluation confirmed the value of in-person training received from scientists. And an ecologist clarified during interviews that for scientists, the interactions with school partners would reveal what experiences were beneficial for students and teachers and how those experiences contributed to the shared goals of the STSP in service of science education and scientific research. Finally, scientists' in-person presence during fieldwork would provide them with insights into how well the fieldwork techniques and rationales were understood by the school partners. This contextual information, in turn, would help scientists to better interpret (and use) student-gathered data.

Materials. To bring this vision to life, the ecologists shared newsletters with teachers to communicate field news about their research, administer surveys to seek teacher input on enhancing their participation and share their experiences with in-class and fieldwork activities, provided (visualizations of) student-gathered vegetation data back to the schools to aid their data analyses activities, and included updates about project timelines and activities. In so doing, as observed during their team meetings, the designers aimed to convey the importance of teacher perspectives in the design process and to offer resources to "create a community" with "mutual give-and-take." There were professional development webinars to clarify the connections among the data sets in the in-class unit, the standardized vegetation fieldwork, and the ecologists' research on bird migration; to offer scientist-led demonstrations of fieldwork techniques; and to gather feedback from teachers. As explained by the curriculum writers during interviews, the webinars also served as a platform to extend the communication with a wider network of schools and nurture "relationship building" among the STSP stakeholders.

These designer attempts at "social engineering" were important because, as a curriculum writer reasoned during interviews, STSPs ran the risk of creating utilitarian relationships if partner scientists were interested in school-based citizen science primarily for obtaining valid data for their research study. In the absence of carefully crafted supports, the school partners may not receive adequate help to "work their way into some experience about undertaking inquiry for themselves as well." Thus, through the newsletters and webinars designed to realize the vision for teacher and scientist participation and elicit their feedback to guide each other's work, the designers hoped to support the stakeholders in actual dialogue and collaboration around the shared goals of science education and scientific research on climate change. The findings on design phases presented below show how the curriculum supports geared towards this particular boundary crossing process were generated by the designers.

5.3.3.3 Design phases

Evaluation. Early in the STSP, upon conducting pilot trials of the standardized fieldwork, the designers noted the value of personal assistance from scientists, as described in the excerpt below in an annual report to the funding agency. Furthermore, to later generate topics and content for the PD webinars (the development of the webinars is elaborated in the next sub-section), designers also drew on their observations and surveys of teacher enactment of the in-class unit and fieldwork, written pre-and- post assessments of students' understanding of the content, and teacher feedback on specific needs and interests related to supplementary fieldwork and data analysis.

> *In many cases the participating teachers didn't really know how to conduct field work, and weren't comfortable or knowledgeable about the natural history of their area. The presence of enthusiastic and knowledgeable naturalists as represented by [partner ecologists] meant that the routine of field work was enriched or enlivened by stories, spontaneous comments about other features noted, and interaction with the naturalist "habits of mind" that make field work stimulating and engaging. Moreover, [partner ecologists] provide a warrant for the authentic value of the field work, which was exciting and motivating for students and teachers alike.*

Development. The designers considered the timing and sequencing of the webinar content, as observed in their team meetings and planning documents. The curriculum writers emphasized beginning with the in-class unit in a fall workshop to help teachers "overcome the barrier of unfamiliarity and feel like they have mastered the curriculum before implementing something new." This would also allow teachers ample time to try the curriculum "as though they were the students," which in turn would yield feedback for the designers. Field techniques would be discussed in a subsequent spring workshop, which would be closer in time to the actual fieldwork enactment.

Instead of a long web-based session, the curriculum writers stressed a series of shorter webinars to address various foci and challenges of the STSP, such as in-class tasks, fieldwork, and student engagement. The general approach was to "offer more than less but in unintimidating chunks." Hence, they proposed a sequence of discrete topics, which would include both canned and live components, all made available online to build towards distance learning and reduce the demands on partner scientists. As a next step, an outline of the webinar components was created. Additionally, teachers recommended including a broadcast from the ecologists to the students because the latter were motivated by "doing science of interest to real scientists." This resulted in a webinar in which the ecologists discussed their research on banding migratory birds and illustrated standardized vegetation fieldwork. The webinars were recorded and the recordings were made available to the teachers.

5.4 Discussion

This participant-observation case study set out to answer the question: How do designers attend to stakeholders' (i.e., students', teachers', and scientists') needs, what curriculum supports do they create, and what methods do they employ during phases of the design process in designing for STSPs to integrate citizen science with school science? In short, the designer work examined in this study aimed to help students, teachers, and scientists in the present STSP to engage in the processes of othering, communicative connection, and continuous joint work to cross boundaries between the cultures of science and schooling. In so doing, the designer decisions in creating various curriculum supports for the stakeholders align with recommendations from prior research specifically for promoting science learning via citizen science and more generally for effective environmental education and science education. The study extends current understandings in the literature by revealing empirical details of designer considerations and measures behind the curriculum supports to incorporate high-quality features. Furthermore, the study contributes to the literature by offering a practical guide that is derived from details of this designer work to aid others in designing for STSPs to integrate citizen science with school science, thereby serving to bridge formal science education with students' everyday lives and society. The guide is presented in Table 5.4 and portrays curriculum supports and design methods to address specific designer considerations for serving the goals and needs of students, teachers, and scientists.

5.4.1 Reflections on designing for STSPs

5.4.1.1 Boundary crossing to understand stakeholder goals and needs

The present STSP exemplifies designer attention simultaneously to multiple goals, needs, and constraints driving boundary crossing processes from the perspectives of the main stakeholders: the school partners and the scientists. Pedagogical goals stressed bringing current, place-based, and thus personally relevant science closer to the science classroom through scientist-designed and supplementary citizen science fieldwork and analyses of authentic data sets. Broad curricular goals focused on the context of climate change for integrating core concepts and disciplinary practices to facilitate standards-aligned science instruction. And finally, there were scientific goals related to the research program(s) specified by partner ecologists and other citizen science projects that motivated the standardized and optional fieldwork projects.

The designer work showed how diverse needs and constraints reflective of the practices of science and schooling were foregrounded in relation to one another to help stakeholders pursue these goals. Designers clarified connections between climate change theory and students' fieldwork via instructional tasks such as readings and discussions, thus tightly linking the fieldwork and in-class components of the STSP curriculum, as recommended in recent research on integrating citizen science with school science (Harlin et al., 2018). In so doing, they attended to local geographic relevance of in-class and fieldwork experiences to make climate change education personally meaningful to the students. Integrating environmental education with local ecosystems surrounding schools has been shown to deepen students' understanding of scientific concepts and processes and their connections to the real world and to promote students' interest in learning science (Lieberman & Hoody, 1998). Engaging with local phenomena was also intended to help understand more global, distant phenomena, both through first-hand experiences via standardized and supplementary fieldwork and second-hand experiences through in-class data analytic and discussion activities focused on students' own data as well as data from other scientific research. Prior research suggests that providing for rich experiences locally first and situating local investigations within a larger (internet-based) network of investigations can help students ultimately develop broader perspectives that integrate more complex scientific concepts (Feldman et al., 2000). The first entry in Table 5.4 is distilled from this designer work to foster connections between local and global phenomena for meaningful and productive student inquiry.

In helping stakeholders cross boundaries between the cultures of science and schooling, the designers also responded specifically to teachers' needs for understanding the background science to facilitate student engagement with data collection and analysis, in turn, and for interacting with partner scientists to help students contribute high-quality data towards scientific research. This attention to teacher needs is crucial because difficulties emerge when students (and teachers) have insufficient understanding of requisite concepts and skills to contribute to the partner scientists' research (Zoellick et al., 2012). The requisite background knowledge for understanding the scientific research program may be far too advanced compared to the school partners' current understandings of the science (Drayton & Falk, 1997, 2006). For instance, the practice of conducting (field) investigations is emphasized in science curricular standards, but it may not be familiar to many students and teachers. The rationales, techniques, and connections between local (school-based) fieldwork and the broader scientific research, while often implicit to scientists, may not be transparent to the school partners.

The designers also attended to stakeholder needs in establishing communicative connections for fieldwork. They considered curricular mandates, conflicting timing of ecological phenomena and school assessments, and limits on teachers' time, providing modular options to help teachers incorporate the in-class unit and fieldwork into different grade levels and subjects as specified by the school curricula. The considerations are crucial because the present science education frameworks emphasize integrating concepts and practices via student investigations involving planning and conduct of data collection, analyses, communication, and so forth (NRC, 2012). However, teachers are typically concerned with aligning the partnership with educational standards (Doubler, 1997), focusing on curricular topics relevant to standardized assessments (Moreno, 2005). Therefore, by attending carefully to these considerations, designers can align the scientific research agenda with the intended student learning outcomes through multiple projects and varied levels of engagement to strengthen the target concepts and skills specified in curriculum frameworks (Zoellick et al., 2012) and as emphasized in recent research (National Academies of Sciences, Engineering, and Medicine, 2018). The second entry in Table 5.4 is based on this designer work to support teachers in enacting citizen science projects within the expectations and constraints of their school settings.

In expanding the fieldwork, the designers also strove to balance scientists' needs for acquiring rigorous student-gathered data via standardized fieldwork experiences, while providing for flexible and varied fieldwork activities to enable teacher enactment and student engagement and learning, thus working towards harmony between the scientific and educational goals of the partnership (Zoellick et al., 2012). This was deemed important to motivate and facilitate students in making valuable contributions to broader citizen science databases. As mentioned earlier, disruptions in collaboration may arise due to differences in the cultures of science and schooling, such as scientists' concerns with data quality and implementing fieldwork protocols and teachers' concerns with aligning the fieldwork with educational standards (Doubler, 1997). For instance, despite the provision of standardized protocols, school partners may contribute low-quality data due to inconsistent implementation stemming from curricular and time constraints (Means, 1998). Another difference is between the time scales of student investigations and scientific research (Barstow, 1997). Whereas the former is generally brief, the latter is often longitudinal to yield meaningful findings but more challenging to sustain student engagement. Additionally, a related challenge is that teachers are expected to not only orchestrate fieldwork within the requirements and limitations of their school settings but also to motivate students for the fieldwork. This is crucial because students' participation is school-based citizen science is non-voluntary, unlike broader citizen science projects in which the general public volunteers to contribute in various ways (Roche et al., 2020). The menu of optional fieldwork projects supplemented the original standardized vegetation fieldwork to yield more short-term findings and a greater variety of contributions focused on different species of potential interest and relevance to school partners, through protocols with different degrees of standardization, thereby aiming to maintain the interest of school partners in the partnership (see Means, 1998, for a similar point about supplementary data analytic activities to address curricular mandates and sustain partnerships).

Furthermore, in supporting stakeholder needs for continuous interactions and negotiations between teachers and scientists, the designers were sensitive to conveying more than simply action items to enact in-class and fieldwork activities. They strove towards a mutual exchange of information by providing teachers with access to scientific expertise and with opportunities to contribute ideas in developing and refining the partnership. These measures may validate the partnership for school partners, who may come to see their involvement as something of real value to science, other than just "doing school." The second entry in Table 5.4 is also formulated through this designer work.

Finally, the study offers insights into how designers may tackle some of the challenges of school-based citizen science programs in promoting students' interest. Specifically, current research shows that students may not feel a strong sense of ownership and contribution to scientific research, possibly because they may perceive their involvement with data collection and analyses simply as participating in curricular tasks (Dohn, 2021). Furthermore, students may feel low motivation if there are few opportunities to personalize the tasks based on their interests and prior experiences (Walkington & Bernacki, 2014). As a result, teachers are tasked with selecting among many possible citizen science initiatives that would enable them to align their educational pursuits (including the promotion of student engagement) with the scientific goals and requirements (Roche et al., 2020). The third entry in Table 5.4 draws on this designer work to nurture scientific and educational aspects of the STSP.

5.4.1.2 Curriculum supports for boundary crossing

These goals and needs were supported through various roles for participation and tasks envisioned for the stakeholders in crossing boundaries and through print and digital materials to bring designer vision to life in the classroom and on the field. Consistent with prior research in science education broadly and citizen science and STSPs specifically, the materials were targeted to the needs and wishes of the different partners. For example, informed by a place-based learning approach, the curricular content was customized to present students with local, familiar species examples through readings and discussions to appeal to their interests and affective engagement. The inclusion of local examples and discussions as part of the in-class tasks reflects current emphases in designing for effective environmental education (Monroe, Plate, Oxarart, Bowers, & Chaves, 2019). The in-class guides provided students and teachers with requisite background knowledge to contribute to scientific research, presenting learning objectives and desired student responses (Schwartz, 2006), educative notes about student conceptions (Roseman et al., 2017), rationales for specific scientific practices (McNeill et al., 2017), such as the target fieldwork techniques, and strategies to engage students in scientific practices (Bismack et al., 2015), such as analyses of authentic data sets. And to make standardized fieldwork accessible and engaging, the rationale and techniques were clarified through in-class guides, videos for instructional support, interactions with scientists in the field and through PD webinars, and structured data sheets and protocols to aid in data collection and reporting, consistent with recent recommendations in the literature specifically for school-based citizen science (Harlin et al., 2018) and more broadly for environmental education (Monroe et al., 2019). The work behind various curriculum supports reported in this study shows how designers may respond to the cultural differences between scientific research and school practice in terms of the background content knowledge and access to resources that different partners bring to the partnership (Tanner et al., 2003), and also how they may address the need for direct interactions with scientists to sustain the interest of school partners, which is difficult due to the demands on scientists' time (Means, 1998).

For STSPs, the design of fieldwork protocols, data sheets, and authentic data sets merits special attention because these serve as standardized methods and boundary objects (Carlisle, 2002; Star & Griesemer, 1989); they are artifacts exchanged between collaborating sites, yet their purpose and significance may be interpreted differently by the partners. For instance, while teachers and students use fieldwork protocols and data sheets to record observations or measurements as part of specific instructional activities, scientists emphasize data quality and rigor in service of broader scientific endeavors, which may not always be apparent to the school partners. Similarly, whereas scientists may view student-gathered data sets as part of larger research programs, teachers may view these as narrower pedagogical tools for student learning and may need guidelines to make sense of specific data sets. The findings of this case study point to ways in which designers may plan towards supporting stakeholders to engage with such boundary objects for both scientific and science educational pursuits.

5.4.1.3 Design methods to create curriculum supports

Finally, the methods across design phases for building this partnership involved inputs (and outputs) from the stakeholders across phases of design, making it an iterative, collaborative process (Penuel et al., 2011). The partner ecologists contributed in multiple ways throughout development and evaluation, offering direct fieldwork assistance to school partners via in-person interactions and webinars and assessing the quality of student-gathered fieldwork data. They provided feedback on framing the scientific research agenda; supplied data sets from their own research; weighed in on suitable scientific content, local examples, and projects through surveys and consultation with other scientists, and on logistics and regional and broader applicability and scientific value of fieldwork tasks to shape curriculum supports. Specific materials created by them - fieldwork protocols and data sheets, instructional resources, and newsletters - also represented their perspective and expertise (Könings et al., 2014). The involvement of the ecologists thus served to provide school partners with access to current scientific knowledge via resources and dialogue, which may help structure and make citizen science investigations attainable for students (Gray et al., 2012). Thus, as recommended in the literature, the ecologists contributed towards reinforcing the scientific authenticity of the envisioned participation and tasks through their feedback on using student-gathered data and towards providing access and supports for working with authentic data (National Academies of Sciences, Engineering, and Medicine, 2018). The teachers offered ideas for webinar topics and reflected on their experiences with implementation to help refine the curriculum supports. Through multiple activities and tools – in-person interactions, written surveys, webinars - they injected into the partnership both teaching and learning considerations, highlighting what was feasible for teachers and meaningful for students (Houseal et al., 2014).

Finally, core to the partnership was the involvement of curriculum writers, who mediated the school-scientist collaboration by drawing on their knowledge of school culture and their scientific training to translate the varied goals and needs into specific requirements and ideas for creating curriculum supports. In so doing, they blended their own insights with the contributions from scientists and teachers at specific points to yield a usable and acceptable intervention (Könings et al., 2007), deriving inspiration and information from various sources: literature; in-person observations and surveys of school implementations; pre-and post-assessments of student learning; interactions with teachers and scientists; and drafts of materials to elicit feedback from stakeholders. The work of the curriculum writers reflects recommendations in the research for cultivating school-scientist partnerships, such as to include a third-party liaison (Houseal et al., 2014; Zoellick et al., 2012); to value the contributions of all partners (Moreno, 2005); and to clarify curriculum-specific science content and practices to help teachers prepare for student inquiry and contribute student-gathered data to scientific research projects (Fishman, Penuel, & Yamaguchi, 2006).

5.4.2 Limitations of the study and recommendations for research

Despite several affordances of the approach used in this study, a few limitations also bear mention. First, as with all case studies, it is difficult to generalize the findings. Further research is needed to gain a broader understanding of designer thinking and action to tackle the challenges of STSPs for integrating citizen science with school science. Second, the present study did not gather data directly from the teachers or students who were also stakeholders in the STSP. In fact, the voices of these stakeholders were conveyed to the researchers only indirectly through the designers. However, including student input directly into the partnership is crucial (Roche et al., 2021) because student perceptions influence the effectiveness of educational interventions (Könings et al., 2014). Hence, future research could gather data directly from students and teachers to understand better how their perspectives and experiences shape the work behind STSPs. Third, while the study did have access to important data on students' learning outcomes, it lacked information on student motivation, teachers' enactment of scientific practices, and the usefulness of student-gathered data for scientific research. As such, the dimensions for which designer success can be claimed are rather limited. Subsequent studies could collect such data to understand better how designer choices shape the attainment of specific educational and scientific outcomes.

Table 5.4: Practical guide to design for STSPs.

Designer Considerations	Sample Curriculum Supports	Design Methods
Blend local with more widely applicable explorations to provide for personally meaningful and academically productive student inquiry.	In-class analyses and discussions of readings and data sets focused on local environmental examples and some national or global examples. Design and conduct field investigations for stand-alone projects motivated by local partnerships and some to feed into broader citizen science projects.	Survey relevant literature; input from scientists to incorporate suitable background information, data sets, and fieldwork to highlight local relevance of the STSP experiences.
Provide appropriate level of support tailored to teachers' knowledge; current practice and needs; and comfort with science content, inquiry, and in collaborating with scientists.	Multiple forms of support to provide complementary and ongoing guidance through in-person and electronic communication with stakeholders, print-based guides, and digital resources to enact in-class and fieldwork tasks.	Survey of teacher (and student) experiences, first-hand observations of implementations, and direct interactions with teachers. Data about student learning through pre-and-post assessments. Input from partner scientists to explain requisite background content.
Supplement core scientist-designed investigations with optional tasks to realize curricular, pedagogical, and scientific value of the partnership.	A toolkit of materials (protocols, data sheets, in-class guides, etc.) for school partners to conduct more and less standardized fieldwork for partner scientists; contribute data towards broader citizen science endeavors; and analyze authentic data sets derived from students' own research and research conducted by partner scientists.	Input from partner scientists to specify the scientific research agenda. Survey existing citizen science programs to incorporate into the research agenda, and feed suitable data sets back to schools.

5.4.3 *Final remarks*

Designing for effective STSPs focused on citizen science is complex because these need to respond to the requirements and constraints of their stakeholders as they cross boundaries between the cultures of schooling and science. This study reveals the challenges and resolutions of designers in providing authentic, educative experiences in environmental education to students and teachers, whilst enabling them to contribute to scientific research. In so doing, the study elucidates key considerations and methods in designing for modular and customizable instructional experiences that can account for variations in geography, students' interests, teachers' preferences, and curricular requirements and constraints. Derived from in-depth empirical analyses and enriched by the broader literature, these detailed insights can inform the efforts of other educators who wish to extend STSPs to a wider spread of school and science partners. In revealing designer reasoning and methods behind scalable STSPs, the study makes the generally tacit designer knowledge visible to novice and experienced designers, yielding a much-needed precedent to inform similar pursuits in integrating citizen science with school science education.

References

Aivelo, T., & Huovelin, S. (2020). Combining formal education and citizen science: A case study on students' perceptions of learning and interest in an urban rat project. *Environmental Education Research, 26*(3), 324-340.

Akkerman, S. F., & Bakker, A. (2011). Boundary crossing and boundary objects. *Review of Educational Research, 81*(2), 132-169.

Akomaning, E. (2019). Improving student internship through collaborative curriculum design: Needs and context analysis to inform the design process. In J. Pieters, J. Voogt, and N. Pareja-Roblin (Eds.), *Collaborative curriculum design for sustainable innovation and teacher learning* (pp. 105 -114). Springer Nature.

Baek, J. S., Kim, S., Pahk, Y., & Manzini, E. (2018). A sociotechnical framework for the design of collaborative services. *Design Studies, 55*, 54-78.

Bakx, A. W. E. A., Bakker, A., Koopman, M., & Beijaard, D. (2016). Boundary crossing by science teacher researchers in a PhD program. *Teaching and Teacher Education, 60*, 76-87.

Ballard, H. L., Dixon, C. G., & Harris, E. M. (2017). Youth-focused citizen science: Examining the role of environmental science learning and agency for conservation. *Biological Conservation, 208*, 65-75.

Barstow, D. (1997). The richness of two cultures. In *National Conference on Student & Scientist Partnerships* (pp. 33-37). Cambridge, MA: TERC and Concord Consortium.

Bismack, A. S., Arias, A. M., Davis, E. A., & Palinscar, A. S. (2015). Examining student work for teacher uptake of educative curriculum materials. *Journal of*

Research in Science Teaching, 52(6), 816-846.

Bonney, R., Ballard, H., Jordan, R., McCallie, E., Phillips, T., Shirk, J., & Wilderman, C. C. (2009). Public participation in scientific research: Defining the field and assessing its potential for informal science education. A CAISE Inquiry Group Report.

Bonney, R., & Dhondt, A. A. (1997). FeederWatch. In *National Conference on Student & Scientist Partnerships* (pp. 64-65). Cambridge, MA: TERC and Concord Consortium.

Bonney, R., Phillips, T., Ballard, H. L., & Enck, J. W. (2015). Can citizen science enhance public understanding of science? *Public Understanding of Science*, 1-15.

Bopardikar, A., Bernstein, D., & McKenney, S. (2021). Designer considerations and processes in developing school-based citizen science curricula for environmental education. *Journal of Biological Education*, 1-26.

Branch, R. M., & Merrill, M. D. (2012). Characteristics of instructional design models. In *Trends and Issues in Instructional Design and Technology* (3rd edition, pp. 8-16). Boston, MA: Pearson.

Carlile, P. R. (2002). A pragmatic view of knowledge and boundaries: Boundary objects in new product development. *Organization Science, 13*(4), 442-455.

Castagneyrol, B., Valdés-Correcher, E., Bourdin, A., Barbaro, L., Bouriaud, O., Branco, M., ... & Tack, A. J. (2019). Can school children support ecological research? Lessons from the 'Oak bodyguard'citizen science project. *Citizen Science, 5*(1), 10.

Cipolla, C., & Manzini, E. (2009). Relational services. *Knowledge, Technology & Policy*, *22*(1), 45-50.

Clarke, J., & Dede, C. (2009). Design for scalability: A case study of the River City curriculum. *Journal of Science Education and Technology*, *18*(4), 353-365.

Condliffe, B., Qunit, J., Visher, M. G., Bangser, M. R., Drohojowska, S., Saco, L., & Nelson, E. (2017). *Project-Based Learning: A Literature Review.* Working Paper. MDRC.

Davis, E. A., Palincsar, A. S., Arias, A. M., Bismack, A. S., Marulis, L., & Iwashyna, S. (2014). Designing educative curriculum materials: A theoretically and empirically driven process. *Harvard Educational Review, 84*(1), 24-52.

Dickinson, J. L., & Bonney, R. (2012). Introduction: Why citizen science?. In J. L. Dickinson & R. Bonney (Eds.), *Citizen Science: Public Participation in Environmental Research* (pp. 1-14). Cornell University Press.

Dohn, N. B. (2021). Predictors of students' interest in a citizen science programme. *International Journal of Science Education*, *43*(18), 2956-2973.

Doubler, S. J. (1997). Two-way partnerships: An introduction to SSPs. *In National Conference on Student & Scientist Partnerships* (pp. 23-26). Cambridge, MA: TERC and Concord Consortium.

Drayton, B., & Falk, J. (1997). What do the ecologists get from an innovative mentoring program with high school teachers? *Bulletin of the Ecological Society of America, 78*(4), 256-260.

Drayton, B., & Falk, J. (2006). Dimensions that shape teacher-scientist collaborations for teacher enhancement. *Science Education, 90*(4), 734-761.

Edelson, D. C. (2002). Design research: What we learn when we engage in design. *Journal of the Learning Sciences, 11*(1), 105-121.

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences, 8*(3-4), 391-450.

Emerson, R. M., Fretz, R. R., & Shaw, L. L. (1995). Writing ethnographic fieldnotes. Chicago: University of Chicago Press.

Fishman, B. J., Penuel, W. R., & Yamaguchi, R. (2006). Fostering innovation implementation: Findings about supporting scale from GLOBE. In S. A. Barab, K. E. Hay, & D. T. Hickey (Eds.), *Proceedings of the 7th International Conference of the Learning Sciences* (Vol. 1, pp. 168–174). Mahwah, NJ: Erlbaum.

Feldman, A., Konold, C., Coulter, B., & Conroy, B. (2000). *Network science, a decade later: The Internet and classroom learning*. Routledge.

Golumbic, Y. N., Baram-Tsabari, A., & Fishbain, B. (2016). Increased knowledge and scientific thinking following participation of school students in air-quality research. In *Proceedings of Indoor Air*.

Goodlad, J. (1994). Curriculum as a field of study. In T. Husén & T. Postlethwaite (Eds.), *The international encyclopedia of education* (pp. 1262-1276). Oxford: Pergamon Press.

Gray, S. A., Nicosia, K., & Jordan, R. C. (2012). Lessons learned from citizen science in the classroom. *Democracy & Education, 20*(2), 1-5.

Guba, E. G. (1981). Criteria for assessing the trustworthiness of naturalistic inquiries. *Educational Communication and Technology, 29*(2), 75-91.

Gustafson, K. L., & Branch, R. M. (2002). What is instructional design? In R, A. Reiser & J. V. Dempsey (Eds.) *Trends and Issues in Instructional Design and Technology* (pp.16-25). Columbus: OH, Merrill Prentice Hall.

Harlin, J., Kloetzer, L., Patton, D., Leonhard, C., & Leysin American School high school students. (2018). Turning students into citizen scientists. In S. Hecker, M. Haklay, A. Bowse, Z. Makuch, J. Vogel, & A. Bonn (Eds.), *Citizen Science: Innovation in Open Science, Society and Policy* (pp. 410-428). UCL Press: London.

He, Y., & Wiggins, A. (2017). Implementing an environmental citizen science project: Strategies and concerns from educators' perspectives. *International Journal of Environmental & Science Education, 12*(6), 1459-1481.

Hedley, M. L., Templin, M. A., Czajkowski, K., & Czerniak, C. (2013). The use of geospatial technologies instruction within a student/teacher/scientist partnership: Increasing students' geospatial skills and atmospheric concept knowledge. *Journal of Geoscience Education, 61*(1), 161-169.

Houseal, A. K., Abd-El-Khalick, F., & Destefano, L. (2014). Impact of a student-teacher-scientist partnership on students' and teachers' content knowledge, attitudes toward science, and pedagogical practices. *Journal of Research in Science Teaching, 51*(1), 84-115.

Howard, C. D., Boling, E., Rowland, G., & Smith, K. M. (2012). Instructional design cases and why we need them. *Educational Technology, 52*(3), 34.

Kelemen-Finan, J., Scheuch, M., & Winter, S. (2018). Contributions from citizen science to science education: An examination of a biodiversity citizen science projects with schools in Central Europe. *International Journal of Science Education, 40*(17), 2078-2098.

Könings, K. D., Brand-Gruwel, S., & Van Merriënboer, J. J. G. (2007). Teachers' perspectives on innovations: Implications for educational design. *Teaching and Teacher Education*, *23*(6), 985-997.

Könings, K. D., Seidel, T., & van Merriënboer, J. J. G. (2014). Participatory design of learning environments: Integrating perspectives of students, teachers, and designers. *Instructional Science, 42*(1), 1-9.

Kruse, R., Howes, E. V., Carlson, J., Roth, K., Bourdelat-Parks, B., Roseman, J. E., & Flanagan, J. C. (2013). Developing and evaluating an eighth grade curriculum unit that links foundational chemistry to biological growth: Changing the research-based curriculum. Paper presented at the *NARST Annual International Conference*, Rio Grande, Puerto Rico, USA.

Lieberman, G. A., & Hoody, L. L. (1998). Closing the achievement gap: Using the environment as an integrating context for learning. Results of a nationwide study. Chicago.

Miczajka, V. L., Klein, A. M., & Pufal, G. (2015). Elementary school children contribute to environmental research as citizen scientists. *PloS one*, *10*(11) e0143229.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook.* Thousand Oaks, California: Sage.

McNeill, K. L., González-Howard, M., Katsh-Singer, R., & Loper, S. (2017). Moving beyond pseudoargumentation: Teachers' enactments of an educative science curriculum focused on argumentation. *Science Education, 101*(3), 426-457.

McKenney, S., & Reeves, T. C. (2019). Conducting educational design research (2nd ed). Routledge.

Means, B. (1998). Melding authentic science, technology, and inquiry-based teaching: Experiences of the GLOBE program. *Journal of Science Education and Technology, 7*(1), 97-105.

Merriam, S. B. (1988). *Case study research in education: A qualitative approach*. Jossey-Bass.

Monroe, M. C., Plate, R. R., Oxarart, A., Bowers, A., & Chaves, W. A. (2019). Identifying effective climate change education strategies: a systematic review of the research. *Environmental Education Research*, *25*(6), 791-812.

Moreno, N. (2005). Science education partnerships: Being realistic about meeting expectations. *Cell Biology Education, 4*, 28-37.

Morse, P. M. (1997). Bridging the gaps and increasing the opportunities for student and scientist partnerships. *In National Conference on Student & Scientist Partnerships* (pp. 19-22). Cambridge, MA: TERC and Concord Consortium.

Mosley, G., Markauskaite, L., Wrigley, C. (2021). Design facilitation: A critical review of conceptualisations and constructs. *Thinking Skills and Creativity, 42*, 100962.

National Academies of Sciences, Engineering, and Medicine. (2018). *Learning through citizen science: Enhancing opportunities by design*. National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, cross-cutting concepts, and core ideas.* Washington D.C.: National Research Council.

Novak, A. M., & Treagust, D. F. (2018). Adjusting claims as new evidence emerges: Do students incorporate new evidence into their scientific explanations?. *Journal of Research in Science Teaching*, *55*(4), 526-549.

Paige, K., Hattam, R., & Daniels, C. B. (2015). Two models for implementing citizen science projects in middle school. *Journal of Educational Enquiry, 14*(2), 4-17.

Penuel, W. R., Fishman, B. J., Haugan Cheng, B., & Sabelli, N. (2011). Organizing research and development at the intersection of learning, implementation, and design. *Educational Researcher*, *40*(7), 331-337.

Phillips, T., Porticella, N., Constas, M. and Bonney, R., 2018. A Framework for Articulating and Measuring Individual Learning Outcomes from Participation in Citizen Science. *Citizen Science: Theory and Practice*, 3(2), p.3. DOI: http://doi.org/10.5334/cstp.126

Rivet, A. E., & Krajcik, J. S. (2004). Achieving standards in urban systemic reform: An example of a sixth grade project-based science curriculum. *Journal of Research in Science Teaching, 41*(7), 669-692.

Roche, J., Bell, L., Galvão, C., Golumbic, Y. N., Kloetzer, L., Knoben, N., Laakso, M., Lorke, J., Mannion, G., Massetti, L., Mauchline, A., Pata, K., Ruck, A., Taraba, P., &Winter, S. (2020). Citizen Science, Education, and Learning: Challenges and Opportunities. *Frontiers in Sociology* 5:613814.

Roseman, J. E., Herrmann-Abell, C. F., & Koppal, M. (2017). Designing for the Next Generation Science Standards: Educative curriculum materials and measures of teacher knowledge. *Journal of Science Teacher Education, 28*(1), 111-141.

Sagy, O., Kali, Y., Hod, Y., Baram-Tsabari, A., Tal, T., & Ben-Zvi, D. (2020). Taking citizen science to school: A mutualistic ecology of science learning. Paper presented at the *European conference for citizen and participatory science 2020*. Trieste, Italy.

Sanders, E. B. N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. *Co-design*, *4*(1), 5-18.

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

Saunders, M. E., Roger, E., Geary, W. L., Meredith, F., Welbourne, D. J., Bako, A., ... & Moles, A. T. (2018). Citizen science in schools: Engaging students in research on urban habitat for pollinators. *Austral ecology*, *43*(6), 635-642.

Schwartz, A. T. (2006). Contextualized chemistry education: The American experience. *International Journal of Science Education, 28*(9), 977-998.

Songer, N. B. (2006). BioKids: An animated conversation on the development of curricular activity structures for inquiry science. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 355-369). New York: Cambridge University Press.

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology, 'translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology. *Social Studies of Science, 19*(3), 387-420.

Tanner, K.D., Chatman, L., and Allen, D. (2003). Approaches to biology teaching and learning: science teaching and learning across the school–university divide: cultivating conversations through scientist–teacher partnerships. *Cell Biol. Educ. 2*, 195–201.

The Globe Program (n.d.), Retrieved on January 10, 2020, from https://www.globe.gov/do-globe/classroom-ready-activities/learning-activities

Thijs, A., & van den Akker, J. (2009). *Curriculum in development*. Enschede: SLO Netherlands Institute for Curriculum Development.

Trautmann, N. M., Shirk, J., Fee, J., & Krasny, M. E. (2012). Who poses the question? Using citizen science to help K–12 teachers meet the mandate for inquiry. In J. L. Dickinson and R. Bonney (Eds.), *Citizen science: Public collaboration in environmental research* (pp. 179-190). Ithaca, NY: Cornell University Press.

Tsui, A. B., & Law, D. Y. (2007). Learning as boundary-crossing in school–university partnership. *Teaching and Teacher Education, 23*(8), 1289-1301.

Van den Akker, J. (2013). Curricular development research as a specimen of educational design research. In T. Plomp and N. Nieveen (Eds.), Educational Design Research (pp. 52-71). Enschede: SLO Netherlands Institute for Curriculum Development.

Van Gog, T., Paas, F., & Merriënboer, J. J. (2004). Process-oriented worked examples: Improving transfer performance through enhanced understandings. *Instructional Science, 32*(1), 83-98.

Walkington, C., & Bernacki, M. L. (2014). Motivating Students by "Personalizing" Learning around Individual Interests: A Consideration of Theory, Design, and Implementation Issues. In S. Karabenick & T. C. Urdan (Eds.), *Motivational Interventions* (pp. 139-176). Bingley: Emerald Group Publishing Limited.

Wiser, M., Smith, C. L., & Doubler, S. (2012). Learning Progressions as tool for curriculum development: Lessons from the Inquiry Project. In Alonzo, A. and Gotwals, A. (Eds.) *Learning Progressions in Science* (pp. 359–403). Boston: Sense Publishing.

Yin, R. K. (2014). *Case study research: Design and methods* (5th edition). Thousand Oaks, California: Sage Publications, Inc.

Zoellick, B., Nelson, S. J., & Schauffler, M. (2012). Participatory science and education: Bringing both views into focus. *Frontiers in Ecology and Environment, 10*(6), Citizen Science – new pathways to public involvement in research, 310-313.

Chapter 6
Conclusion

This chapter synthesizes and discusses the main findings from the sub-studies of the dissertation, which was guided by three research objectives (ROs), namely: to identify designers' rationales, considerations, and (team) processes for creating curricula that can deepen students' learning via real-world contexts (RO-A); to identify how designers' rationales, considerations, and (interdisciplinary team) processes create educative curriculum materials with the potential to support teachers' learning (RO-B); and to identify how curriculum materials, designers' considerations, and (team) processes are geared towards supporting (enablers of) persistence in curriculum enactment (RO-C). First, the purpose and overall approach of the study will be revisited, followed by a summary of key findings resulting from each sub-study. Next, for each RO, the main findings will be synthesized and discussed in light of relevant literature. The chapter closes with reflections on the limitations of the study, followed by recommendations for curriculum design research, practice, and policy, as well as the contributions of the study towards science education.

This study aimed to understand designers' reasoning and processes behind scalable science curricula. High-quality curricula are crucial to the realization of the current vision in science education reform initiatives~~,~~ which emphasize instruction in fundamental scientific ideas and practices through active student (and teacher) engagement (e.g., Australian Curriculum, Assessment, and Reporting Authority, 2010; NRC, 2012; National curriculum in England: Science programmes of study, 2015). This vision is advocated for all students, which requires science curricula to serve instructional settings marked by different needs, preferences, and constraints. But designing for scale is complex because it requires supporting deep student learning to help them integrate and apply scientific ideas and disciplinary practices through which scientific knowledge is constructed. To this end, curricula situated in authentic contexts are advocated, such as in engineering design-based projects inspired by career settings (Vickers, 1998) and in citizen science projects (Bonney et al., 2016). However, whereas authentic contexts can motivate students, these may not always engage them cognitively (Blumenfeld et al., 2006), and students may lack requisite content knowledge to participate productively (Zoellick et al., 2012). In essence, authentic contexts need to address content that is not only appealing to students' interests but that also meets important learning goals framed in curricular expectations and is relevant to real-world problems in communities or workplaces (Blumenfeld et al., 2006; Krajcik & Blumenfeld, 2006).

Furthermore, it requires supporting deep teacher learning – their views (i.e., knowledge and beliefs about the subject matter, student learning, pedagogy, etc.) and enactment of the pedagogical principles underlying the curriculum - to achieve students' integration and application of scientific ideas and practices through an inquiry-based approach. Whereas educative curriculum materials can support teachers (Bismack et al., 2015), creating such materials is difficult. The materials need to clearly specify curricular goals and the teacher's role (Fullan, 2016; McKenney & Reeves, 2019), yet also promote teachers' autonomy in making adjustments during enactment (Cohen & Ball, 1999; Drayton et al., 2020). Further, educative supports need to target multiple interconnected components of teachers' learning, such as their knowledge of the subject, of student thinking, and of instructional strategies (Davis & Krajcik, 2005; Magnusson et al., 1999; Park & Chen, 2012), which calls for a strategic orchestration of diverse expertise during the design process.

Finally, to support teachers' learning (and ultimately students' learning), designers also need to achieve persistence in curriculum enactment, so that curricula can be used across time and instructional settings. This is challenging because it requires designers to pay attention to multiple dimensions of persistence – shift, sustainability, and spread – and to curriculum characteristics that can enable the dimensions. Specifically, the curriculum needs to: provide added value over existing curricula; be tolerant to adaptations made by teachers; be compatible with school policies, concerns, and capabilities; and be clear in helping teachers envision and perform their role in enacting the curriculum (Blumenfeld et al., 2000; McKenney & Reeves, 2019).

The available literature offers guidance on generic models and processes of curriculum and instructional design; on heuristics and principles for designing science curricula; and on features of high-quality science curricular products. But the research literature offers limited insights into designers' reasoning and action that can yield science curricula contextualized in (engineering design) careers and citizen science to deepen students' learning; that can create educative curriculum materials through interdisciplinary expertise to support teachers' learning; and that can promote (enablers of) persistence in curriculum enactment (i.e. added value, tolerance, compatibility, and clarity, as described in Chapter 1). Given these gaps in the literature, three research objectives (ROs) were formulated to frame the dissertation:

- **RO-A (Students' learning):** To identify designers' rationales, considerations, and (team) processes for creating curricula that can deepen students' learning via real-world contexts. In this study, 'students' learning' refers to students' ability to integrate and apply key scientific ideas and practices in contexts where the subject matter is typically used.
- **RO-B (Teachers' learning):** To identify how designers' rationales, considerations, and (interdisciplinary team) processes create educative curriculum materials with the potential to support teachers' learning. In this study, 'teachers' learning' pertains to their views and enactment of pedagogical principles underlying the curriculum.
- **RO-C (Enactment persistence):** To identify how curriculum materials, designers' considerations, and (team) processes are geared towards supporting (enablers of) persistence in curriculum enactment. In this study, 'persistence' is

characterized by shift in ownership, sustained use, and spread of the curriculum materials and underlying ideas.

A qualitative multiple case study approach was undertaken to pursue the ROs collectively, resulting in a set of four sub-studies. Each sub-study investigated a single curriculum and yielded in-depth description and analysis of designers' reasoning and action behind the curriculum design initiative (Merriam, 2002; Yin, 2014). Furthermore, there was a blend of retrospective and participant-observation approaches across sub-studies. Through this mix of approaches the author was able to develop worked examples (van Gog et al., 2014) capturing designers' reflections on finished curriculum products (Howard et al., 2012) and their responses to emergent needs, preferences, and constraints of students and teachers (Emerson et al., 1995; Yin, 2014).

Each RO was pursued through three or more of these sub-studies (see Table 1.1 in Chapter 1 for a visual overview of sub-studies in relation to the ROs and case study approaches). Sub-studies 1, 3, and 4 contributed to RO-A, which was to identify designers' work for deepening students' learning. Sub-studies 2, 3, and 4 contributed to RO-B, which was to identify designers' work behind educative curriculum materials for deepening teachers' learning. All four sub-studies contributed to RO-C, which was to identify designers' work for supporting (enablers of) persistence in curriculum enactment.

The remainder of this chapter is organized as follows. First, an overview of the key findings of each sub-study is presented. Next, the findings across sub-studies are integrated and discussed in view of the pertinent literature for each RO. The chapter then notes the strengths and limitations of the study and offers research, practice, and policy recommendations for curriculum design. In closing, the chapter comments on the main contributions of this study and its wider significance for the science education field.

6.1 Key findings

6.1.1 Overviews per sub-study

Sub-study 1 focused on designers' processes and decisions in creating a work-based high school physics curriculum that supported learning of key concepts and practices among students with broad academic and vocational interests, especially those who intended to join the workforce and were less inclined to pursue post-secondary science education. Qualitative analysis of the data gathered retrospectively from semi-structured interviews with curriculum designers (n = 6), from their planning documents, and from the commercially published written curriculum portrayed designer work behind situating students' learning in suitable career contexts. Learning limited standards-aligned content deeply via workplace contexts was prioritized in the intended outcomes and vision for enactment and reinforced in the teacher and student materials through storylines, sequences of activities and milestones, relevant conceptual and procedural information, and questions to enact design-and-build projects in class and interactions with workplace professionals. Designers' processes enabling work-based contextualization involved a variety of measures across phases of design, such as survey of curricular needs in schools; review of relevant occupational information and other science curricula; workplace visits to learn about authentic work-based praxis; expert appraisal; and pilot test data to iteratively revise supports for both understanding the science and the workplace connections. Through process and product guidelines stemming from these findings and the literature, this study exemplified and highlighted designers' attention to content that is core to both science curricular frameworks and workplaces; to integrating workplace context across curriculum representations; to providing teachers with both strategies and background information; and to evaluation processes centered on science content, instruction, and workplace connections.

Sub-study 2 focused on interdisciplinary design processes behind the creation of a longitudinal elementary grade educative curriculum aimed at helping teachers understand and enact scientific concepts and inquiry-based practices. Qualitative analysis of the data gathered retrospectively from semi-structured interviews with designers (n = 6), from their planning documents, and from curriculum materials elucidated how designers undertook the complex endeavor of producing a coherent curriculum with various educative features that can support teachers' pedagogical content knowledge (PCK) for integrating concepts and practices. The design team, composed of a cognitive psychologist, a practicing physicist, and science educators, worked collaboratively to invite and integrate different kinds of specialized input from its members during the phases of analysis, development, and evaluation, based on their respective disciplinary expertise. The findings revealed the varied nature of designers' contributions aimed at different PCK components. Designers made both proactive contributions (producing outputs aimed at specific PCK components, such as knowledge of subject matter, student thinking, instructional strategies, etc., and/or implementing specific design measures) and reactive contributions (providing feedback on outputs generated by team members). The collaborative interdisciplinary design work was also characterized by intermeshing, in which outputs created by designers from one disciplinary background were specified and made possible by proactive and/or reactive contributions from designers of another background, blending together to result in coherent educative features. Additionally, emerging from the data was the importance of collaboratively created artifacts – boundary objects – to shape the design team's negotiations and decisions. Throughout phases of design, the melding of diverse disciplinary contributions enabled designers to address multiple PCK components iteratively and in tandem. The study offered recommendations, distilled from these empirical findings and inspired by the broader literature, for research and practice to help other designers in interdisciplinary teams make choices in eliciting proactive and reactive contributions according to PCK components and to facilitate intermeshing of varied disciplinary contributions towards all PCK components and during different design phases.

Sub-study 3 examined designers' reasoning and processes in creating a curriculum to help middle school students learn about climate change through a school-based citizen science context. Qualitative analysis of the data gathered through participant-observation of design team meetings, planning documents, and curriculum materials, and semi-structured interviews with designers (n = 4) brought to light their challenges, measures, and decisions as they strove to integrate in-class curriculum with citizen science fieldwork: designing for fieldwork that is meaningful for students’ learning, feasible for teachers’ implementation, and rigorous for scientific contribution; preparing students with foundational scientific understanding to conduct suitable fieldwork; and supporting teachers’ understanding and enactment of scientific concepts and practices. Designers' vision for enacting in-class and fieldwork activities and the written materials for students and teachers was in the service of achieving outcomes centered on helping students understand key scientific practices, climate science concepts, and the value of local citizen science initiatives in building knowledge about climate change. Across phases of design, designers' work to tackle the challenges was shaped through various means, such as expert appraisal of the treatment of in-class curricular content and its alignment with the fieldwork; local expertise and inspiring examples of citizen science projects and phenology frameworks; observations and surveys of teachers' implementation, students' engagement, and student-gathered fieldwork data; and pre-post assessments of student understanding. Process and product considerations were derived from these findings and informed by the broader literature, in order to aid other designers pursuing similar endeavors, namely, equipping students and teachers with scientific understanding by situating fieldwork and data analyses in foundational scientific theory; mitigating concerns about the quality and utility of student-gathered data via multiple supports for fieldwork; motivating students to engage with scientist-designed fieldwork by strengthening connections between fieldwork and scientific research; and balancing scientific and educational goals by expanding fieldwork opportunities for students.

Sub-study 4 examined designers’ considerations and methods in service of a scalable Student-Teacher-Scientist-Partnership (STSP) aimed at helping students and teachers to understand concepts and practices while participating in authentic inquiry with partner scientists and contributing to research on climate change, including other citizen science projects. Participant-observation over multiple years enabled data collection from semi-structured interviews with designers (n = 4), from observations of their team meetings, and from their planning documents and curriculum materials. Qualitative analysis of the data indicated how the design team, composed of curriculum writers and ecologists, tackled the challenges of supporting STSP stakeholders – in this case, the ecologists themselves and students and teachers from local middle schools – to cross boundaries between the cultures of science and schooling. Designers attended to diverse stakeholder needs, preferences, and constraints related to pedagogical, curricular, and scientific goals as they sought to help the stakeholders engage in specific boundary crossing processes. To that end, designers also took specific measures to generate a vision for participation and to generate in-class, fieldwork, and teacher professional development tasks and materials to help the scientist and school partners enact the vision. The findings point to the value of inviting inputs and outputs from the STSP stakeholders – ecologists and teachers – during specific design phases to iteratively and collaboratively design for the partnership, in addition to the specific contributions and expertise of curriculum writers in mediating the partnership.

Drawing on these findings and in light of the broader literature, the study offered practical guidelines to aid other designers of scalable STSPs in nurturing productive students' inquiry; in providing appropriate guidance to teachers; and in accomplishing both scientific and science educational goals.

6.1.2 RO-A: Students' learning

Sub-studies 1, 3, and 4 contributed to identifying designers' rationales, considerations, and processes for deepening students' learning via real-world contexts (RO-A). Despite the emphasis on contextualized curricula for promoting students' understanding of scientific ideas and practices (Krajcik & Blumenfeld, 2006), there is little detailed knowledge of underlying designers' reasoning and measures, especially for creating curricula situated in engineering design careers and citizen science. The present study addresses this gap.

6.1.2.1 Tasks and materials for students

Across sub-studies, multiple in-class and out-of-class tasks, including class discussions pertaining to engineering design-based projects contextualized in career settings (sub-study 1) and citizen science projects (sub-studies 3 and 4) intended to help students integrate and apply target scientific ideas and practices in authentic contexts. Furthermore, students' interactions with STEM practitioners in sub-study 1 and with practicing ecologists in sub-studies 3 and 4 were envisaged to motivate students' science learning and to reinforce their content understanding. To enact these tasks, the written materials were situated in authentic and locally relevant problems and praxis and organized around a central theme. In sub-study 1, a storyline wove together activities and conceptual knowledge within workplace scenarios for each unit. In sub-study 3, the materials prioritized local examples of species to relate the content to students' everyday lives and organized around the theme of signal vs. noise detection served to help students appreciate the importance of long-term data sets and thereby relate this practice to their own fieldwork. Across sub-studies, background conceptual and procedural information was included to help students engage with the content.

The projects centered on problems, concepts, and practices relevant to workplace praxis and scientific research and reflected a commitment to providing opportunities characterized by authenticity, academic rigor, active learning, and access to relevant practitioner expertise. These features are crucial yet difficult to orchestrate in crafting meaningful and productive student projects (Steinberg, 1998). The designer rationales, considerations, and processes found in these sub-studies thereby offer insights for balancing authentic contexts with important disciplinary content and for motivating and facilitating student learning. The remainder of this sub-section unpacks designers' reasoning and action behind these tasks and materials.

6.1.2.2 Designers' rationales

Four key designer rationales emerged from the study. The designers wanted to address content that was both academically rigorous to frame productive inquiry and appealing to motivate the inquiry. Further, contexts clearly relevant to students' lives were prioritized to situate the content in meaningful settings. Student projects served to connect science theory with practice, thus integrating core concepts and practices. Finally, the projects modeled authentic practice and clarified the nature and utility of science, for instance, how data are generated and analyzed, how concepts can inform design decisions or fieldwork, and how scientific knowledge can address real-world problems.

6.1.2.3 Designers' considerations

Several considerations shaped the tasks and materials. For productive student inquiry, depth over breadth of science content coverage was emphasized, treating limited concepts aligned with curriculum frameworks. To make the inquiry meaningful, designers chose local contexts that were visible to students - workplaces related to technical careers accessible in local settings (sub-study 1) and climate change as it manifested in students' local surroundings (sub-studies 3 and 4). Furthermore, to make the (integration of) scientific ideas and practices accessible through these contexts, designers stressed projects in which students would have first-hand experiences with relevant praxis. Finally, improving students' access to practitioners was important to reinforce their understanding of how the content was actually applied to tackle real-world problems.

6.1.2.4 Designers' processes

Various measures served to contextualize the tasks and materials. The analysis phase (in sub-study 1) centered on surveys to assess curricular needs and to formulate an initial vision of the content and pedagogy. Surveys continued in the development phase across sub-studies to select suitable contexts for the target content. In sub-study 1, they helped select appropriate occupations and unit topics to represent in the curriculum; examine strengths and limitations of other curricula; and investigate work sites to understand authentic praxis. These measures are vital to ensure that the content is both core to the scientific discipline to promote academically productive learning and pertinent to the contexts of students' inquiry (Blumenfeld et al., 2006; Krajcik & Blumenfeld, 2006). In sub-studies 3 and 4, surveys focused on ecological information drawn from a prior project and from other regional frameworks and citizen science programs to include in the written materials. These measures are thus also important to choose contexts and tasks that are potentially meaningful to a broad range of students (Blumenfeld et al., 2006). Furthermore, the familiarity of local settings may help invite initial student ideas and questions about the underlying science, while the connections to their personal lives and communities may make the tasks and scientific phenomena compelling to promote student engagement and understanding (Rinehart et al., 2016). Additionally, during the development phase, input from practitioners helped contextualize the content. In sub-study 1, professional technicians clarified workplace praxis, whereas in sub-studies 3 and 4, practicing scientists advised on authentic data sets, conceptual information, and fieldwork projects. Additionally, sub-study 4 revealed teachers' input to facilitate students' access to scientists.

In the evaluation phase, designers drew on pilot data to include additional tasks and supports. In sub-study 1, they noted connections made by workplace professionals between science content and praxis, students' responses to workplace visits, and their challenges with specific disciplinary practices to iteratively refine the vision and written materials. External appraisal of content coverage and work-based contextualization revealed a need for deepening content treatment and strengthening workplace connections. In sub-study 3, external appraisal focused on depth of content treatment, purpose of fieldwork, and its alignment with in-class learning. And teachers' feedback inspired designers to generate additional materials for in-class (data analysis) and supplementary fieldwork activities.

These measures thus helped the designers work towards promoting students' engagement with data, which is a critical scientific practice yet difficult to facilitate because its essential elements are often tacit to novices (Edelson & Reiser, 2006). The process also helped the designers balance student ownership in conducting projects with feasibility and academic rigor (Krajcik & Blumenfeld, 2006), which was especially pertinent to the citizen science context in sub-studies 3 and 4. Finally, the process enabled the designers to orchestrate the purpose, timing, and supports for students' interactions with STEM practitioners. In so doing, they considered the focus of the interactions, their perceived benefits and limitations, and their timing in relation to other instructional activities. These insights are pertinent because students' exposure to STEM practitioners is valued (Gray et al., 2012; Marginson et al., 2013; Steinberg, 1998; Zoellick et al., 2012; Vickers, 1998), yet there is little guidance for orchestrating this kind of exposure to models of authentic practice. This study shows how designers can take specific steps to provide students with meaningful, productive, and timely interactions with STEM practitioners.

Figure 6.1 synthesizes the main findings related to RO-A; it depicts curricular tasks and materials created for students to achieve this objective and highlights key designer rationales, considerations, and processes that yielded these materials.

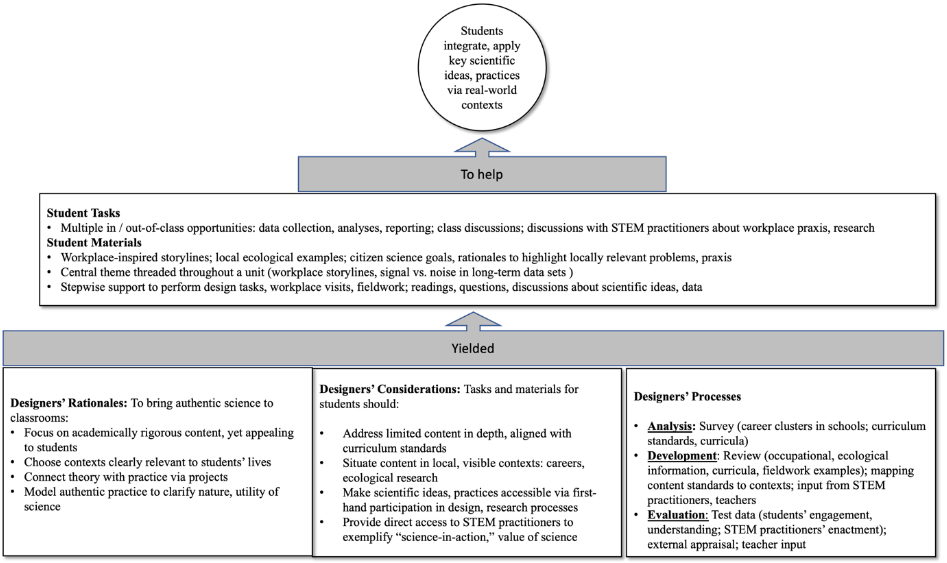


Figure 6.1: Designers' work for students' learning.

6.1.3 RO-B: Teachers' learning

Sub-studies 2, 3, 4 contributed to identifying designers' rationales, considerations, and processes in (interdisciplinary) team work for creating educative curriculum materials with the potential to support teachers' learning (RO-B). Educative curricula can promote both teacher and student learning. But this type of curricula are difficult to generate because designers need to serve multiple interconnected components of teacher learning simultaneously, which calls for interdisciplinary expertise. This study elucidates how designers crafted educative materials through a blend of inputs and outputs from scientific and science educational perspectives, including external feedback from experts and teachers.

6.1.3.1 Educative materials

The educative materials addressed teachers' views and enactment of pedagogical principles by elucidating meaning and importance of the target scientific ideas and practices, the underlying pedagogical approach, and students' typical conceptions and difficulties. The materials also presented instructional strategies and procedural guidance through stepwise information to enact in-class and fieldwork tasks. These features appeared through a combination of background and lesson-embedded information and were geared towards promoting teachers' capability, that is, their conceptual and practical knowledge for enacting the curriculum (Blumenfeld, Fishman, Krajcik, Marx, & Soloway, 2000). The remainder of this sub-section portrays designers' work which brought these materials to fruition.

6.1.3.2 Designers' rationales

The study revealed three main designer rationales behind the educative materials. To address potential limitations in teachers' experience with (enacting) scientific practices and access to scientists, it was important to make the science understandable and familiar to teachers (and ultimately to students). Doing so meant clarifying the meaning of the target science content, its importance to the scientific discipline, and its relevance in the real world. Another rationale was to capture how scientists engage with the ideas and practices to make their reasoning more accessible to teachers. Finally, designers stressed communicating a vision of scientific inquiry in classrooms to help teachers (and ultimately students) integrate scientific ideas and practices.

6.1.3.3 Designers' considerations

A number of considerations guided the design of the materials. First was assisting teachers during both planning and in-the-moment, as manifest through a combination of background information and specific guidance for use during enactment. Second, the designers stressed balancing foundational content with what was pedagogically valuable for student learning and feasible for teacher enactment. In sub-study 2, designers considered schools' science and mathematics curriculum expectations, students' prior mathematical knowledge, teachers' time constraints, and critical scientific ideas to promote in service of the ultimate learning goal of the curriculum. In sub-study 3, to accommodate teachers' time constraints, a reduced content coverage focused on core yet difficult ecology content that was not addressed in other subject areas, was necessary to contextualize and motivate students' fieldwork, and was related to the practice of collecting and analyzing long-term data sets. Sub-study 4 elaborated this consideration by noting how designers expanded fieldwork projects to respond to teachers' requirements, preferences, and constraints.

A third consideration was making scientists' perspectives visible via print and/or digital media, exemplified in sub-study 2 through scientist essays explaining the meaning and importance of the content. On this note, in sub-studies 3 and 4, there was an in-class teacher guide clarifying fieldwork rationales, instructional videos, and webinars communicating scientific expertise on the fieldwork purposes and techniques.

A fourth consideration was coherence among curricular goals, content, and tasks. In sub-study 2, this was reflected in background overviews and lesson-embedded narratives highlighting a sequence of investigations and learning goals. In sub-studies 3 and 4, a written guide and webinars clarified how the fieldwork and long-term data sets were informed by foundational climate science theory and served scientific research on climate change (as represented in the in-class materials). By communicating curricular coherence, the designers thus conveyed their pedagogical approach for enacting inquiry. This explication was important because teachers and curriculum designers may have different notions about scientific inquiry in classrooms (Crawford, 2007). For example, teachers may associate cookbook investigations and pre-packaged, disconnected hands-on activities with inquiry (McLaughlin & MacFadden, 2014; Moscovici & Nelson, 1998). Therefore, addressing this divergence is important because while teachers may use new curriculum materials, changes in their pedagogical approach and in their perspectives are crucial to achieve the desired curricular goals (Coburn, 2003; Fullan, 2016).

A fifth consideration was detailing structures and roles to help teachers enact inquiry through first-hand investigations, engagement with data, and discussions. Sub-study 2 exemplified a consistent tripartite structure for lesson-wise investigations, while sub-study 3 recounted guidelines for collecting, preparing, and interrogating data sets. The written guides revealed how questions, examples, or explanations and conceptual information were specified to help teachers use appropriate language for integrating scientific ideas and practices.

These are important considerations because teachers may have limited preparation for helping students conduct scientific inquiry, and perhaps may lack experience with and understanding of disciplinary practices themselves (Crawford, 2007). Additionally, teachers' understanding of science and their perspectives about learning as inquiry are interrelated and shape their teaching through inquiry (Anderson, 2002). Therefore, designers need to address teachers' knowledge and beliefs as such, within the practical context of their classrooms.

Finally, in clarifying teachers' actions for enacting the curriculum, there was a fair degree of specification, offering guidance on content, tasks, and student and teacher participation (McKenney & Reeves, 2019). At the same time, formative assessments in sub-study 2 and supplementary fieldwork in sub-studies 3 and 4 point to potential adjustments for responding to teachers' and students' needs. Thus, the present study exemplifies designers' work in specifying and developing curricula to guide teachers (and ultimately students), while also allowing for teachers' autonomy in instructional decisions (Cohen & Ball, 1999).

6.1.3.4 Designers' processes

There was an interplay of inputs and outputs based on diverse areas of designer expertise to generate the educative materials. The contributions addressed teachers' views and enactment in tandem, including their knowledge and beliefs related to the subject matter, student thinking, and instructional strategies. In so doing, curriculum writers served as "brokers," bridging between scientific inquiry and classroom pedagogy. They translated scientific expertise into vision and materials that were pedagogically meaningful and feasible. In sub-study 2, an interdisciplinary mix of contributions came from a cognitive psychologist, a physicist, and science educators, with the third group itself representing a combination of subject matter knowledge and expertise in relevant grade-level teaching and design of science curriculum and teacher professional development. In sub-studies 3 and 4, this mix occurred through contributions of practicing ecologists and curriculum writers, with the latter bringing both knowledge of ecology and experience with science curriculum design. Additionally, there was feedback from external sources, namely, teachers in sub-study 2 and project advisers and teachers in sub-study 3.

The analysis phase in sub-study 2 included reviewing (and refining) prior work done by the cognitive psychologist and science educators to articulate a vision for teaching through inquiry. The development phase in sub-study 2 included input from the physicist and cognitive psychologist to clarify the subject matter and students' understandings respectively in generating scientist and child essays. The cognitive psychologist also contributed towards formative assessments and grade-level sequences of content drafted by the science educators. The science educators, in turn, reviewed assessments frameworks, video, and students' written work mined from the curriculum project, drafted specific materials, and provided initial ideas and feedback to their team. Additionally, teachers provided feedback to craft assessment materials. In sub-study 3, the ecologists worked with curriculum writers to select suitable data sets for supporting teachers' data analytic activities. They also clarified the research agenda behind the fieldwork and expanded assistance through video tutorials. And in sub-study 4, the ecologists created newsletters to share relevant scientific information.

The evaluation phase yielded data on teachers' enactment and students' engagement and understanding. In sub-study 2, the science educators observed classroom enactment, and the cognitive psychologist conducted clinical interviews with students, generating insights for supporting teachers' understanding of instructional strategies and student thinking. Sub-studies 3 and 4 described how the ecologists and curriculum writers scrutinized teachers' (and students') needs and challenges through their observations of fieldwork enactment and teacher surveys. The ecologists also examined the quality of student-gathered data, while the curriculum writers examined students' conceptual understandings through written assessments, which similarly shaped designer work for supporting teachers' understanding of instructional strategies and student thinking. Finally, in sub-study 3, project advisers and teachers suggested refinements in the materials to address specific teacher needs in enacting in-class and fieldwork tasks. This study thus shows how interdisciplinary contributions across design phases can help designers craft educative materials with the potential to support teachers' views and enactment of the underlying pedagogical principles.

Figure 6.2 synthesizes the main findings related to RO-B; it depicts the educative materials and highlights designers' rationales, considerations, and processes that yielded these materials through interdisciplinary teamwork.

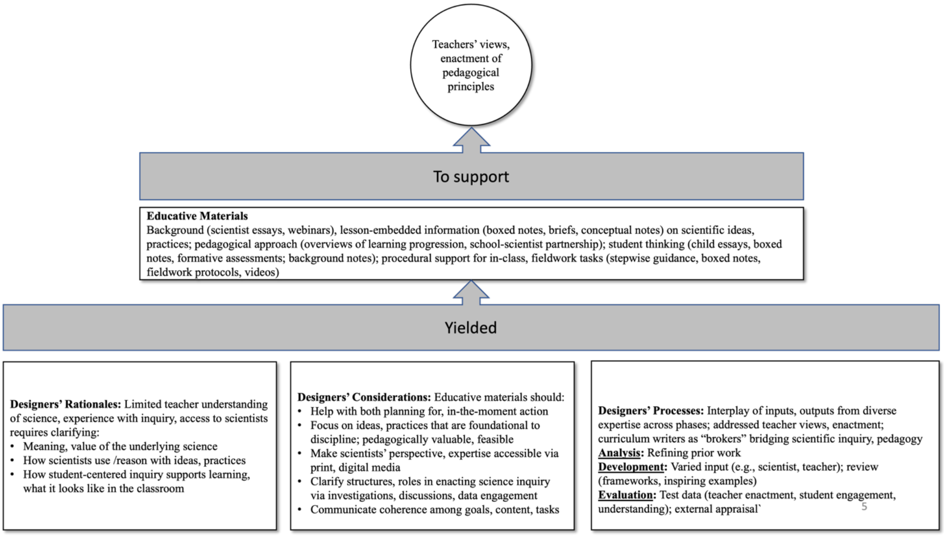


Figure 6.2: Designers' work for teachers' learning.

6.1.4 RO-C: Enactment persistence

All four sub-studies contributed to identifying how curriculum materials, designers' considerations, and (team) processes are geared towards supporting (enablers of) persistence in curriculum enactment (RO-C). Whereas specific curriculum designs may be suitable for supporting students' and teachers' learning, the designs also need to be practicable to yield persistent enactment and ultimately positive impact in varied settings. The study shows how curriculum materials were shaped by various considerations and processes that address dimensions of persistence (shift, sustainability, and spread) and their enablers. The findings across sub-studies are first synthesized and discussed here with reference to each dimension so as to highlight the underlying designer considerations and processes behind specific materials. This discussion is followed by a portrayal of how this designer work reflects attention to the enablers of persistence.

6.1.4.1 Shift

Sub-studies 2, 3, and 4 contributed to understanding *designers' considerations* for the shift dimension. The teacher guides provided detailed information to plan and enact inquiry-based instruction. The main designer considerations were to empower teachers with options, requisite background knowledge, and in-the-moment tools to facilitate and adapt inquiry in-class (sub-studies 2, 3, and 4) and on the field (sub-studies 3 and 4). In sub-study 2, in the formative assessments offered pointers to interpret students' ideas and plan next steps, thus designed to help teachers adjust their teaching moves based on emerging student understandings and difficulties. The supplementary fieldwork materials in sub-studies 3 and 4 provided tips for projects based on students' interests and local surroundings.

The development phase of the *design process* centered on reviewing frameworks and examples to derive criteria and procedures for formative assessments in sub-study 2 and for supplementary fieldwork projects and data analytic activities in sub-studies 3 and 4. Inputs and outputs for these were generated through diverse disciplinary expertise, including teachers' input. Furthermore, varied disciplinary expertise continued in the evaluation phase. In sub-study 2, specific educative supports were added, based on the science educators' observations of pilot trials and the cognitive psychologist's findings during field tests. In sub-study 3, teachers provided feedback for revising in-class and fieldwork tasks and materials. In sub-studies 3 and 4, curriculum writers and ecologists observed challenges with standardized fieldwork and used these insights to guide the design of supplementary fieldwork projects.

6.1.4.2 Sustainability

Sub-studies 3 and 4 contributed to understanding *designers' considerations* for the sustainability dimension. The teacher and student guides provided overall structures and stepwise guidance for in-class and fieldwork activities. Educative notes clarified the subject matter and students' thinking. Additionally, sub-study 3 reported video tutorials on fieldwork techniques, while sub-study 4 reported professional development webinars for addressing goals and challenges of enactment. These materials embodied pedagogical and scientific assistance for continued enactment as designers sought to diversify fieldwork and supports for teachers, taking into account various resources and constraints. Specifically, the timing of the standardized fieldwork vis à vis the timing of school assessments was an important consideration, as was school location to ensure fieldwork implementation in a variety of physical spaces. The feasibility of data collection and its value to broader research programs was crucial to sustain schools' engagement with citizen science and longitudinal data sets. Finally, the time constraints for teachers and scientists were considered, with different fieldwork projects and webinars aimed at reducing the demands on scientists' time for in-person assistance, while ensuring teachers continued to receive requisite support to enact projects of their choosing.

6.1.4.3 Spread

Sub-studies 1 and 4 contributed to our understanding of *designers' considerations* for the spread dimension. The student and teacher guides provided guidance for in-class and out-of-class tasks (workplace visits in sub-study 1 and fieldwork projects in sub-study 4), contextualized in a variety of career scenarios (sub-study 1) and local ecological exemplars (sub-study 4). To make the content and tasks relevant to schools in various locations, curriculum expectations about substantive content were considered. Furthermore, in sub-study 1, designers considered careers having broad appeal and prioritized in work-based curricula of schools from different states. They also stressed representing nationally prevalent and readily accessible occupations. In sub-study 4, designers considered tailoring the in-class content to geographical regions of the schools to foster students' association with their local environments and to relate better to scientific research in those regions. Finally, in expanding fieldwork projects to serve schools in different regions, the designers emphasized feasibility in different physical spaces and transferability of projects to wider regions. And they considered connections to national citizen science programs to ensure broader value of student-gathered data and opportunities to explore national databases.

The analysis phase of the *design process* involved surveys of careers represented in work-based courses and of state and national curriculum frameworks (sub-study 1). The development phase included measures to generate relevant and feasible content and tasks. In sub-study 1, designers derived specifications for representing occupations, based on a survey of occupational information and its mapping to content standards. In sub-study 4, designers reviewed regional ecology, phenology, and citizen science program information to include locally relevant content and fieldwork options. In so doing, ecologists offered input on ecological contexts, content, and contributions to citizen science programs.

6.1.4.4 Enablers of persistence

The study reveals designers' attention to key intervention characteristics that can enable dimensions of persistence discussed before (McKenney & Reeves, 2019). One enabler is the *added value* of a curriculum for helping teachers bring authentic science (and engineering) into science classrooms, which is crucial to support spread and shift. Across all sub-studies, the curricula were relevant and timely for integrating and applying scientific ideas and practices, and thus enacting the vision for science education as emphasized in curriculum frameworks in the United States.

Additionally, the perceived usefulness of a curriculum is crucial for its end-users (Michel-Verkeke & Spil, 2013). For example, the curriculum in sub-study 1 responded to schools' demand for work-based science curricula to support students with a broad range of academic and vocational inclinations in completing high school science courses. Further, to develop ownership of a curriculum, teachers need to perceive it as useful for supporting students' learning, for their own instructional practice, and for their professional learning (Fishman et al., 2011). This need was addressed through materials aimed at supporting teachers' understanding of the subject matter, student thinking, instructional strategies, and the underlying pedagogical vision (as reported in sub-studies 2, 3, and 4). The materials thus potentially offered both perceptible and experiential benefits to teachers and ultimately to students (McKenney & Reeves, 2019).

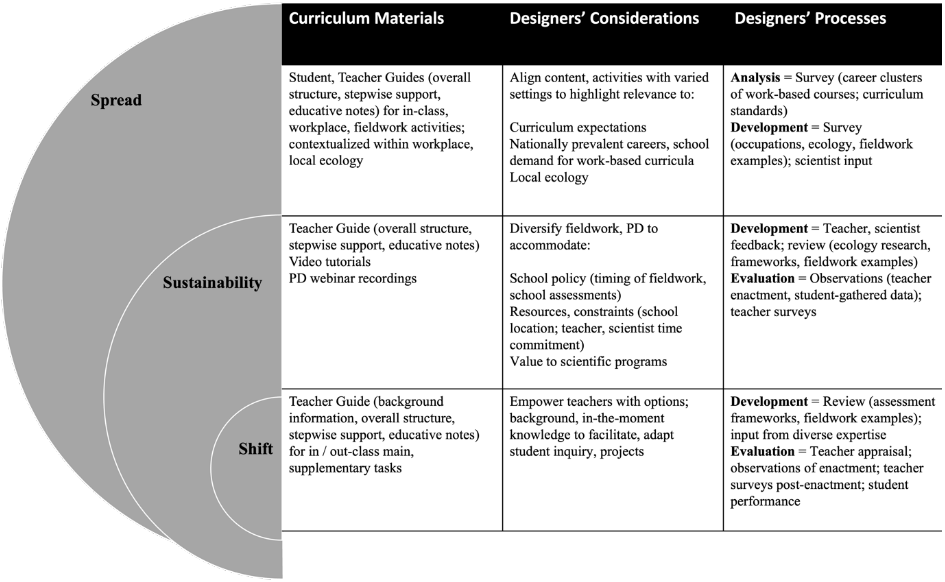
A second enabler is *tolerance* in relation to curricular adaptations. The educative materials described in sub-studies 2, 3, and 4 aimed to enhance teachers' knowledge and options for making instructional decisions and adaptations, thereby intending to promote shift in ownership and ultimately sustainability, as external assistance from designers fades over time. The written guides clarified background knowledge and the underlying pedagogical approach and offered stepwise assistance, and while also providing for choices through tips provided in formative assessments (sub-study 2), and flexibility in choosing supplementary fieldwork (sub-studies 3 and 4).

This kind of curricular flexibility is important to help teachers develop ownership and make adaptations to serve their own instructional contexts (Squire et al., 2003). The designer work thus appears to have emphasized integrity in enactment, in which teachers make adaptations during implementation that are consistent with the designers' goals and vision (Miller et al., 2021; Penuel, Phillips, & Harris, 2014). To that end, embedded formative assessments can offer optimal strategies for promoting sustainability, as teachers may use assessment data to tailor instruction to student progress, thereby reducing their reliance on external designers for feedback about students' learning (Clarke & Dede, 2009). Finally, the combination of explicit guidance coupled with opportunities for teachers' discretion in these materials reflects a designer approach for building teachers' capacity to conduct scientific inquiry, providing them with necessary educative support while creating room for teachers' agency (Drayton et al., 2020). The considerations and processes reported in this study thus show how designers can create adaptive materials while also striving for usability (Cohen & Ball, 1999; Fishman & Krajcik, 2003) to foster sustained use in a variety of settings.

A third enabler is the *compatibility* between curricular requirements and the priorities, expectations, and needs of school partners, which is important to promote sustainability and spread. Sub-study 1 showed how designers worked towards aligning curricular content with the expectations in national and state science education frameworks as well as with work-based science courses demanded by schools. Sub-studies 3 and 4 revealed how educative materials addressed teachers' capacity in terms of their prior experiences and knowledge to provide them with requisite conceptual and procedural assistance for engaging with fieldwork and authentic data. Specifically, school policy, constraints related to standardized assessments, and demands on teachers' time were taken into account for providing greater flexibility in enactment.

These designer decisions may aid in closing the gap between curricular requirements, user capacity, and school policy to yield usable curricula (Blumenfeld et al., 2000). Additionally, a key finding emerging from this study is that compatibility also needs to be considered in relation to the external surroundings of school settings, especially for contextualized curricula involving out-of-class tasks, such as visits to worksites and fieldwork. The designers considered the fit between curricular activities and the broader surroundings in which schools were located. In sub-study 1, they considered nationwide prevalence and accessibility of occupations to represent in the curriculum, while in sub-study 4 (and to a lesser extent in sub-study 3), they considered local ecological environments and fieldwork timing and location to modify in-class materials and expand fieldwork activities.

Finally, *clarity* is a crucial enabler to achieve all three dimensions of persistence, aimed at helping teachers understand their role in implementing the curriculum. And to that end, the designers' thinking reflects attention to curricular content, instructional activities, and the teacher's role to tackle potential premature modifications during enactment (Thijs & van den Akker, 2009). As noted across all sub-studies, the curriculum materials contained background and lesson-embedded supports elucidating science content and students' thinking, the underlying pedagogical approach, and stepwise procedures to help teachers understand the importance and coherence of the target content and tasks and to envisage and take desired action in facilitating students' learning. Figure 6.3 synthesizes the main findings related to RO-C; it depicts curriculum materials, designers' considerations, and (team) processes intended at (enablers of) curricular persistence.



	Curriculum Materials	Designers' Considerations	Designers' Processes
Spread	Student, Teacher Guides (overall structure, stepwise support, educative notes) for in-class, workplace, fieldwork activities; contextualized within workplace, local ecology	Align content, activities with varied settings to highlight relevance to: Curriculum expectations Nationally prevalent careers, school demand for work-based curricula Local ecology	**Analysis** = Survey (career clusters of work-based courses; curriculum standards) **Development** = Survey (occupations, ecology, fieldwork examples); scientist input
Sustainability	Teacher Guide (overall structure, stepwise support, educative notes) Video tutorials PD webinar recordings	Diversify fieldwork, PD to accommodate: School policy (timing of fieldwork, school assessments) Resources, constraints (school location; teacher, scientist time commitment) Value to scientific programs	**Development** = Teacher, scientist feedback; review (ecology research, frameworks, fieldwork examples) **Evaluation** = Observations (teacher enactment, student-gathered data); teacher surveys
Shift	Teacher Guide (background information, overall structure, stepwise support, educative notes) for in / out-class main, supplementary tasks	Empower teachers with options; background, in-the-moment knowledge to facilitate, adapt student inquiry, projects	**Development** = Review (assessment frameworks, fieldwork examples); input from diverse expertise **Evaluation** = Teacher appraisal; observations of enactment; teacher surveys post-enactment; student performance

Figure 6.3: Designers' work for enactment persistence.

6.2 Reflections

6.2.1 Limitations of the study

Specific limitations of each sub-study are discussed in the individual chapters reporting those sub-studies. This chapter discusses the main limitations across the four sub-studies in light of the three ROs. First, as is characteristic of the case study approach, the findings may have limited generalizability to designers' work underlying other kinds of science curricula designed for large-scale use. Investigations of those curricula may reveal different designer challenges, considerations, and measures to tackle the challenges. Second, the study did not scrutinize links between specific designer decisions manifested in the intended curriculum and the achieved scale outcomes related to students' learning, teachers' learning, and persistence in curriculum enactment. For example, the study did not examine whether all features of the written curriculum as reported contribute (equally) to positive outcomes, or are some features more strongly associated with positive outcomes. Third, whereas designers' perspectives were captured in depth, the study did not capture perspectives of teachers and students who participated in curriculum implementation through pilot and field tests. This limitation bears mention because designers, teachers, and students often view educational interventions with different perspectives, which may influence implementation and effectiveness (Könings et al., 2014). Thus, the study did not examine how designers attended to possible divergence in perspectives while iterating on the curriculum.

6.2.2 *Recommendations*

6.2.2.1 For curriculum design research

Whereas the present study captured designers' perspectives, future research should enrich this line of inquiry by including teachers' and students' perspectives as the target end users of curriculum to expand upon designers' descriptions of the intended curriculum and the underlying reasoning and action. For example, sub-study 1 showed how students' responses to workplace visits during pilot testing helped designers finetune their vision for enacting the visits and highlight connections to career contexts. And sub-study 2 indicated that teachers provided feedback on formative assessment criteria for interpreting students' thinking. Inclusion of such teacher and student perspectives could clarify how multiple perspectives are integrated during the design process to support deep student learning, deep teacher learning, and persistence in curriculum enactment. These additional data could be gathered through interviews, documents, and/or observations.

Furthermore, while the present study focused on the intended curriculum, the inquiry should be extended to uncover links between designers' decisions as represented in specific features of the intended curriculum and the attained outcomes related to depth and curricular persistence. As an illustration, consider the variety of background and lesson-embedded educative supports reported in sub-study 2 and how boxed notes were added in lesson plans following evaluation to clarify students' thinking, instructional strategies, and the subject matter. Examining the links between designers' intentions and the attained outcomes would reveal which curriculum features are associated with positive impact at scale (for example, see Pareja Roblin et al., 2018). And it could also spur research about the implemented curriculum, such as to investigate teachers' uptake of the educative supports and how it influences depth and the dimensions of persistence. This extended inquiry could be conducted through observational data, self-reports about curriculum usage from teachers, and data on teachers' and students' learning outcomes.

Finally, subsequent research should extend the present inquiry by investigating how designers learn from and incorporate adaptations made by teachers (potentially in response to their own and to their students' needs and interests, school policy and culture, etc.), thereby rethinking the underlying design and making subsequent decisions through which the curricular innovation evolves (Clarke & Dede, 2009). For instance, sub-study 4 revealed how designers noted challenges and limitations in the original standardized fieldwork, and as a result, developed a broader, adaptable menu of fieldwork options to serve the requirements, constraints, and needs of school settings. But how might designers' thinking and action evolve in response to teachers' actual adaptations of fieldwork options? To answer questions such as this one, interviews could probe designers to reflect on their logic and process behind implemented curricular adaptations, supplemented with specific artifacts capturing the (reification of their) decisions.

6.2.2.2 For curriculum design practice

Since this study highlighted how contributions from different disciplinary backgrounds yield scalable curricula with the potential to support (teachers') learning, curriculum design teams should strive to nurture inputs and outputs from a variety of disciplinary expertise and do so in ways that enable those contributions to generate a coherent curriculum product. For example, to craft key curricular outputs, proactive or reactive inputs should be sought from team members based on their area of expertise and the phase of the design process. Additionally, shared design artifacts could be used as boundary objects to communicate interdisciplinary perspectives (Flood et al., 2015). The use of boundary objects was exemplified in sub-study 2, which portrayed how the design team used a collaboratively-created framework on learning progressions to negotiate design choices about curricular content and shape associated outputs.

Furthermore, design teams should centrally include curriculum writers who bring deep knowledge of both the subject matter and pedagogy, thus serving to bridge authentic science with the realities of the science classroom. This was evidenced in the contributions of the science educators in sub-study 2 and of the curriculum writers in sub-studies 3 and 4. Feedback should also be gathered externally on the pedagogy, content, and its contextualization in real-world problems and praxis. For example, sub-study 1 reported how feedback from the funding agency helped designers deepen the content coverage and strengthen workplace connections in the curriculum units. And sub-study 3 showed how feedback from advisers similarly helped designers deepen the content treatment, motivate the fieldwork, and improve its alignment with the in-class curriculum. Such external input could be acquired through appraisal of curriculum prototypes during the evaluation phase.

Finally, designers should consistently incorporate practitioners' perspectives on subject matter and school implementation. STEM practitioners within and/or outside the core design team could be invited during analysis and development to clarify the meaning, importance, and applications of key scientific ideas and authentic praxis. To illustrate, sub-study 1 found that interactions with professionals during workplace visits yielded important insights into workplace praxis and scientific knowledge applications of various career contexts. And sub-study 2 found how the physicist helped identify a suitable focus for a grade-level unit, and crafted scientist essays to help teachers understand the subject matter. Finally, teachers' perspectives could be sought throughout the design process to shape the intended curriculum in response to the needs, requirements, and constraints of various implementation contexts. To exemplify, consider sub-studies 3 and 4 which reported how teachers provided input during analysis, development, and evaluation to help designers condense the in-class curriculum, craft supplementary materials for in-class and fieldwork activities, and generate supports for professional development.

6.2.2.3 For curriculum design policy

The present study reveals the meticulous and challenging processes of designing scalable curricula that can yield positive outcomes for students and teachers. Consistent with the broader literature, the findings especially highlight the importance of (planning for) a long and iterative design process to generate curricular products that respond to the emergent needs, wishes, and constraints of the end users. This in turn will require generous financial support to equip designers with adequate time and resources to obtain and incorporate feedback from key stakeholders, including teachers and funding agencies.

6.2.3 Contribution of the study

This study unpacked designers' reasoning and processes behind scalable science curricula. Individual sub-studies offer detailed examples of and theoretical and practical implications for designer rationales, considerations, and processes in generating high-quality scalable science curricula. Furthermore, across sub-studies, designers' thinking has been made explicit through clear precedents of designers' processes linked to the designed curriculum products (Lawson, 2004), thereby responding to calls in the wider instructional design field to generate detailed design cases (Howard et al., 2012). Indeed, designers' thinking and measures behind impactful curricula generally reside as tacit knowledge within individual designer work or in the cultures of educational institutions. These are seldom the subject of rigorous empirical investigations, as compared to research on features, enactment, and impact of final curriculum products. Thus, designers' expertise has been made more accessible to other designers through depictions of the intended curricula and their underlying design processes articulated in the study.

In so doing, the study has yielded useful and provocative knowledge about designers' reasoning and strategies to create scalable curricula, grounded in empirical findings and examples and informed by the broader literature. The findings reveal how designers set out to support students and teachers in varied settings, attending to their needs, preferences, and constraints to tackle complex multiple dimensions of scale (Coburn, 2003). This knowledge can thus aid other designers interested in similar endeavors for supporting all students to participate actively and to integrate and apply scientific knowledge, as envisioned in science education reforms today (e.g., NRC, 2012).

Finally, over the course of this study (2014-2023), other educational designers have investigated models, factors, strategies, or outcomes in designing large-scale interventions in international settings, such as for digital technological innovations (Howard, Schrum, Voogt, & Sligte, 2021), for technology-based curricula (Looi, Sun, Wu, & Ye, 2015), and for collaborative curriculum design in teacher teams (e.g., Bakah, Nihuka, & Anto, 2019). The present study makes a small but noteworthy contribution to continue this line of work by presenting more fine-grained insights into designers' thinking and action for creating specific types of contextualized science curricula and educative materials for use at scale. Designing scalable science curricula is a complex enterprise, and the findings of this study offer a way forward to tackle its multiple challenges in supporting students' learning, teachers' learning, and persistent curriculum use.

References

Anderson, R. (2002). Reforming science teaching. What research says about inquiry? *Journal of Science Teacher Education, 13,* 1–12.

Australian Curriculum, Assessment and Reporting Authority. (2012). *National Report on Schooling in Australia 2010*. Sydney: ACARA.

Bakah, M. A. B., Nihuka, K. A., & Anto, A. G. (2019). Fostering the sustainability and scalability of curriculum innovations through collaborative design. In J. Pieters, J. Voogt, & N. Pareja Roblin (Eds.), *Collaborative curriculum design for sustainable innovation and teacher learning* (pp. 331-345). Springer.

Bismack, A. S., Arias, A. M., Davis, E. A., & Palinscar, A. S. (2015). Examining student work for teacher uptake of educative curriculum materials. *Journal of Research in Science Teaching, 52*(6), 816–846.

Blumenfeld, P., Fishman, B. J., Krajcik, J., Marx, R. W., & Soloway, E. (2000). Creating usable innovations in systemic reform: Scaling up technology-embedded project-based science in urban schools. *Educational Psychologist*, *35*(3), 149-164.

Blumenfeld, P. C., Kempler, T. M., & Krajcik, J. S. (2006). Motivation and cognitive engagement in learning environments. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 475–488). New York, NY: Cambridge University Press.

Bonney, R., Phillips, T. B., Ballard, H. L., & Enck, J. W. (2016). Can citizen science enhance public understanding of science? *Public Understanding of Science*, *25*(1), 2-16.

Clarke, J., & Dede, C. (2009). Design for scalability: A case study of the River City curriculum. *Journal of Science Education and Technology, 18*(4), 353-365.

Coburn, C. E. (2003). Rethinking scale: Moving beyond numbers to deep and lasting change. *Educational Researcher*, *32*(6), 3-12.

Cohen, D. K., & Ball, D. L. (1999). *Instruction, capacity, and improvement.* CPRE Research Report Series RR-43. Philadelphia, PA: Consortium for Policy Research in Education, University of Pennsylvania.

Crawford, B. A. (2007). Learning to teach science as inquiry in the rough and tumble of practice. *Journal of Research in Science Teaching*, *44*(4), 613-642.

Davis, E. A. & Krajcik, J. S. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher*, *34*(3), 3-14.

Drayton, B., Bernstein, D., Schunn, C., & McKenney, S. (2020). Consequences of curricular adaptation strategies for implementation at scale. *Science Education*, *104*(6), 983-1007.

Edelson, D. C., & Reiser, B. J. (2006). Making authentic practices accessible to learners: Design challenges and strategies. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 335-354). New York: Cambridge University Press.

Emerson, R. M., Fretz, R. I., & Shaw, L. L. (1995). Writing ethnographic fieldnotes. Chicago: The University of Chicago Press.

Fishman, B. J., & Krajcik, J. (2003). What does it mean to create sustainable science curriculum innovations? A commentary. *Science Education*, *87*(4), 564-573.

Fishman, B., Penuel, W. R., Hegedus, S., & Roschelle, J. (2011). What happens when the research ends? Factors related to the sustainability of a technology-infused mathematics curriculum. *Journal of Computers in Mathematics and Science Teaching*, *30*(4), 329-353.

Flood, V. J., Neff, M., & Abrahamson, D. (2015). *Boundary interactions: resolving interdisciplinary collaboration challenges using digitized embodied performances*. In T. Koschmann, P. Häkkinen, & P. Tchounikine (Eds.), Exploring the material conditions of learning: opportunities and challenges for CSCL, the Proceedings of the Computer Supported Collaborative Learning (CSCL) Conference (Vol. 1, pp. 94-101). Gothenburg, Sweden: ISLS.

Fullan, M. (2016). *The new meaning of educational change* (5th edition). New York: Teachers College Press.

Gray, S. A., Nicosia, K., & Jordan, R. C. (2012). Lessons learned from citizen science in the classroom. *Democracy & Education, 20*(2), 1-5.

Howard, C. D., Boling, E., Rowland, G., & Smith, K. M. (2012). Instructional design cases and why we need them. *Educational Technology, 52*(3), 34.

Howard, S. K., Schrum, L., Voogt, J., & Sligte, H. (2021). Designing research to inform sustainability and scalability of digital technology innovations. *Educational Technology Research and Development*, *69*, 2309-2329.

Könings, K. D., Seidel, T., & van Merriënboer, J. J. G. (2014). Participatory design of learning environments: Integrating perspectives of students, teachers, and designers. *Instructional Science, 42*(1), 1-9.

Krajcik, J. S., & Blumenfeld, P. C. (2006). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 317–333). New York: Cambridge University Press.

Looi, C. K., Sun, D., Wu, L., & Ye, X. (2015). Seeding a curricular innovation from one school to five schools: a case study from Singapore. In C-K. Looi & L. W. Teh (Eds.), *Scaling Educational Innovations* (pp.151-178). Springer: Singapore.

Marginson, S., Tytler, R., Freeman, B., & Roberts, K. (2013). *STEM: Country comparisons. Report for the Australian Council of Learned Academies*. Melbourne, Australia.

Michel-Verkerke, M. B., & Spil, T. A. M. (2013). The USE IT-adoption-model to predict and evaluate adoption of information and communication technology in healthcare. *Methods of Information in Medicine*, *52*(06), 475-483.

Miller, E. C., & Krajcik, J. S. (2019). Promoting deep learning through project-based learning: A design problem. *Disciplinary and Interdisciplinary Science Education Research*, *1*(7), https://doi.org/10.1186/s43031-019-0009-6

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teacher. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge* (pp. 95–132). Kluwer.

McKenney, S., & Reeves, T.C. (2019). *Conducting educational design research*. London: Routledge.

McLaughlin, C. A., & MacFadden, B. J. (2014). At the elbows of scientists: Shaping science teachers' conceptions and enactment of inquiry-based instruction. *Research in Science Education*, *44*, 927-947.

Merriam, S. B. (2002). Introduction to qualitative research. In S. B. Merriam (Ed.), *Qualitative research in practice: Examples for discussion and analysis.* Jossey Bass.

Moscovici, H., & Nelson, T. H. (1998). Shifting from activitymania to inquiry. *Science and Children*, *35*(4), 14–17.

National curriculum in England. Science programmes of study (2013, September 11). Retrieved March 2020, from https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study/national-curriculum-in-england-science-programmes-of-study

National Research Council (NRC). (2012). A framework for K-12 science education: Practices, cross-cutting concepts, and core ideas. National Research Council: Washington D.C.

Pareja Roblin, N., Schunn, C., & McKenney, S. (2018). What are critical features of science curriculum materials that impact student and teacher outcomes? *Science Education*, *102*(2), 260-282.

Park, S., & Chen, Y. C. (2012). Mapping out the integration of the components of pedagogical content knowledge (PCK): Examples from high school biology classrooms. *Journal of Research in Science Teaching*, *49*(7), 922–941.

Penuel, W. R., Phillips, R. S., & Harris, C. J. (2014). Analysing teachers' curriculum implementation from integrity and actor-oriented perspectives. *Journal of Curriculum Studies*, *46*(6), 751-777.

Rinehart, R., Duncan, R., Chinn, C., Atkins, T., & DiBenedetti, J. (2016). Critical design decisions for successful model-based inquiry in science classrooms. *International Journal of Designs for Learning*, *7*(2), 17-40

Squire, K. D., MaKinster, J. G., Barnett, M., Luehmann, A. L., & Barab, S. L. (2003). Designed curriculum and local culture: Acknowledging the primacy of classroom culture. *Science Education*, *87*(4), 468-489.

Steinberg, A. (1998). Real learning, real work: School-to-work as high school reform. New York: Routledge.

Thijs, A., & van den Akker, J. (2009). *Curriculum in development*. Enschede: SLO Netherlands Institute for Curriculum Development.

Van Gog, T., Paas, F., & Merriënboer, J. J. (2004). Process-oriented worked examples: Improving transfer performance through enhanced understandings. *Instructional Science, 32*(1), 83-98.

Vickers, M. (1998). Working to learn: Building science understandings through work-based learning. In A. Steinberg (Ed.), *Real learning, real work: School to work as high school reform* (pp. 109-127). New York: Routledge.

Yin, R. K. (2014). *Case study research: Design and methods* (5th edition). Thousand Oaks, California: Sage Publications, Inc.

Zoellick, B., Nelson, S. J., & Schauffler, M. (2012). Participatory science and education: Bringing both views into focus. *Frontiers in Ecology and Environment: Citizen Science – new pathways to public involvement in research, 10(6),* 310-313.

Nederlandse Samenvatting

Hoe ontwerpers schaalbare bètacurricula creëren

In het bètaonderwijs zijn vernieuwingen uitgevoerd om leerlingen en hun docenten te ondersteunen bij het actief betrekken van fundamentele concepten en handelingen. Om deze visie te realiseren zijn hoogwaardige curricula cruciaal die geschikt zijn voor een breed scala aan leerlingen en docenten. als. Het creëren van dergelijke curricula is een uitdaging omdat ontwerpers op diepgaande wijze het leren van leerlingen moeten ondersteunen bij het integreren en toepassen van wetenschappelijke ideeën en handelingen. Op zijn beurt vraagt dit om het ondersteunen van diepgaand leren van docenten om hetzelfde uit te voeren. Bovendien wordt dit laatste beïnvloed door curriculaire volharding, dat wil zeggen de mate waarin materialen een blijvende invloed hebben door het eigenaarschap van docenten bij het nemen van onderwijsbeslissingen en -aanpassingen te bevorderen; door de uitvoering vast te houden, zelfs als de professionele ontwikkeling in de loop van de tijd vervaagt; en door het gebruik te verspreiden buiten de eerste veldtestlocaties. Terwijl de bestaande literatuur kenmerken van hoogwaardige (bèta)curricula benadrukt, evenals algemene modellen voor het ontwerpen van curriculum en instructie, is er meer nodig. Met name de empirische basis voor veel literatuur over de processen van ontwerpers is vrij beperkt. Er is zeer weinig werk dat het denken en de processen weergeeft van deskundige ontwerpers die succesvolle curricula opleveren, en er is bijna geen onderzoek naar deze kwesties met betrekking tot curricula die zijn ontworpen voor grootschalig gebruik. Als gevolg hiervan is er weinig expliciete kennis om ontwerpers te begeleiden bij het begrijpen en creëren van specifieke curriculaire ontwerpen om de visie van vernieuwing in het bètaonderwijs te verwezenlijken. Om deze lacune op te vullen, volgde het huidige proefschrift daarom een kwalitatieve aanpak met meerdere casestudy's om gezamenlijk drie onderzoeksdoelstellingen na te streven, gericht op het identificeren van de beweegredenen, overwegingen en processen van ontwerpers voor: het ondersteunen van diep leren van leerlingen; voor het ondersteunen van het leren van docenten via educatief materiaal; en voor het ondersteunen van volharding in de uitvoering van het curriculum. Om deze doelstellingen te bereiken, onderzochten vier deelstudies het werk van ontwerpers achter schaalbare curricula die positieve resultaten hadden opgeleverd voor studenten en/of docenten. De deelstudies onderzochten het werk van ontwerpers aan een natuurkundecurriculum op een middelbare school; op een curriculum van de basisschool over materie; en op een ecologiecurriculum op de middelbare school. De deelonderzoeken bieden samen concrete precedenten, implicaties en richtlijnen om ontwerpers te helpen aandacht te besteden aan belangrijke overwegingen en maatregelen ter ondersteuning van diepgaand leren van leerlingen, diepgaande leren van docenten en volharding in het curriculum. Het proefschrift wordt afgesloten met aanbevelingen voor onderzoek, praktijk en beleid op het gebied van curriculumontwerp.

English Summary

How Designers Create Scalable Science Curricula

Science education reforms for schools envision supporting all students and teachers to engage actively with foundational concepts and practices. Crucial to realizing this vision are high-quality curricula that can serve a broad range of students and teachers. But creating such curricula is challenging because designers need to support deep student learning in integrating and applying scientific ideas and practices, which in turn calls for supporting deep teacher learning to enact the same. Furthermore, the latter is influenced by curricularpersistence, i.e., the extent to which materials have lasting influence by promoting teachers' ownership in making instructional decisions and adaptations; by sustaining enactment even as professional development fades over time; and by spreading in use beyond initial field test sites. Whereas the existing literature does highlight features of high quality (science) curricula as well as general models for designing curriculum and instruction, more is needed. Specifically, the empirical basis for much of the literature on designers' processes is quite limited. There is very little work which depicts the thinking and processes of expert designers with track records for yielding successful curricula, and there is almost no research on these issues with regard to curricula designed for large-scale use. As a result, there is little explicit knowledge to guide designers in understanding and creating specific curricular designs to achieve the vision of science education reforms. Hence, to fill this lacuna, the present dissertation followed a qualitative multiple case study approach to collectively pursue three research objectives focused on identifying designers' rationales, considerations, and processes for: supporting deep student learning; for supporting teacher learning via educative materials; and for supporting persistence in curriculum enactment. To achieve these objectives, four sub-studies investigated designers' work behind scalable curricula that had attained positive outcomes for students and/or teachers. The sub-studies examined designers' work on a high school physics curriculum; on a primary school curriculum on matter; and on a middle school ecology curriculum. The sub-studies together provide concrete precedents, implications, and guidelines to help designers attend to key considerations and measures for supporting deep student learning, deep teacher learning, and curricular persistence. The dissertation concludes with recommendations for curriculum design research, practice, and policy.

Scientific Output

Peer-reviewed Journal Articles

Bopardikar, A., Bernstein, D., & McKenney, S. (in press). Boundary crossing in student-teacher-scientist-partnerships: Designer considerations and methods to integrate citizen science with school science. *Instructional Science*.

Bopardikar, A., Bernstein, D., & McKenney, S. (2021). Designer considerations and processes in developing school-based citizen science curricula for environmental education. *Journal of Biological Education*, 1-26.

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2021). Designing educative curriculum materials in interdisciplinary teams: Designer processes and contributions. *Instructional Science, 49*(2), 249-286.

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2020). Work-based curriculum to broaden learners' participation in science: Insights for designers. *Research in Science Education, 50*(4), 1251-1279.

Conference paper and poster presentations

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2017, November 6-9). *Leveraging designers' expertise to create curriculum for teachers' professional growth.* Poster presented at the 13th annual conference of the International Society for Design and Development in Education, University of California, Berkeley, CA, USA.

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2016, September 19-22). Citizen science *in the classroom: Curricular ideas, written materials, and design processes.* Poster presented at the 12th annual conference of the International Society for Design and Development in Education, Utrecht, the Netherlands.

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2015, September 22-25). *Transforming authentic contexts into educative experiences in science: A retrospective case study of designing large-scale curriculum for authentic learning.* Paper presented at the 11th annual conference of the International Society for Design and Development in Education, University of Colorado, Boulder, USA.

Bopardikar, A., Bernstein, D., Drayton, B., & McKenney, S. (2014, September 29-October 2). *Meeting the challenges of designing for scale: Emergent insights from a retrospective case study.* Poster presented at the 10th annual conference of the International Society for Design and Development in Education, University of Cambridge, UK.

Acknowledgements

This dissertation is the culmination of support from numerous individuals, whose wisdom and blessings have steered its course. I am grateful to my supervisor Professor Susan McKenney for taking me under her wings and guiding me gently and patiently throughout this process. Susan's advice helped me develop confidence to persist on this long academic journey. Through my interactions with her, I have come to appreciate the importance of balancing a systematic approach with creativity to tackle research problems and life in general.

I am so thankful to my co-supervisors and colleagues at TERC Brian Drayton and Debra Bernstein for nurturing my interest and for offering me opportunities to expand and deepen my understanding. Over the course of many conversations with them, I have had the good fortune of learning from their collective expertise and rich experiences in this field. I could not have asked for a better team of supervisors to guide me on the doctoral path.

I express my gratitude to TERC for enabling me in various ways to pursue this goal. My former mentor Sue Doubler encouraged me to persist with this commitment despite competing responsibilities. President Laurie Brennan and colleagues in CSTL and SEEC supported the publications through generous funds and general advice for balancing work and life. I take this opportunity to also acknowledge the support from my colleagues on the Design Dimensions project. Chris Schunn, Jacqueline Barber, Natalie Pareja Roblin, and Sara Walkup provided invaluable input in shaping the publications of this dissertation.

My prior education in India and at the University of Wisconsin in Madison, USA, helped me build a solid academic foundation. My interactions with my adviser Professor Sadhana Puntambekar, with other faculty, and with my peers there sparked my curiosity about educational research and equipped me to embark on a much longer journey.

My family has always been a guiding force in my life, and for that I shall be eternally grateful. My parents Dattaprasad and Pradnya have been my most inspiring teachers, whose dedication and perseverance I strive to emulate in my own work. I thank my brother Shaunak and his wife Dhanashree for the many delightful conversations about teaching and learning that I have enjoyed in their company. I am also blessed to have parents-in-law who supported my aspirations. My brother-in-law Ashish and his wife Arathi nourished me with spirited discussions and scrumptious meals as I pursued this goal.

No number of words can adequately convey my deep gratitude towards my husband Raghu. This dissertation could not have seen the light of day had it not been for his sagacity, unflinching support, and unwavering faith in my abilities. From assisting with the minutiae of formatting manuscripts to more general advice about doctoral research and life, he has been an equal partner in this endeavor. And last but not least, I thank my little boy Archis for cooperating with me throughout all those early mornings and late nights that went into writing this dissertation. His presence has imbued my life with a new meaning and hope for the future.

ISBN 978-90-365-5682-8