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Structuring Integrated STEM Education Professional Development: Challenges Revealed and Insights Gained from a Cross-Case Synthesis

Sarah B. Bush
University of Central Florida

Margaret J. Mohr-Schroeder
University of Kentucky

Kristin L. Cook
Bellarmine University

Christopher R. Rakes
University of Maryland Baltimore County

Robert N. Ronau
Johns Hopkins University

Jon Saderholm
Berea College

ABSTRACT

Integrated STEM PD has challenges unique from those normally faced by single-discipline PD. The purpose of this validation study was to examine the effectiveness of the PrimeD framework to guide and improve integrated STEM professional development (PD). Three federally funded PD programs in the United States, focused at different grade bands K-12, were examined using a qualitative cross-case synthesis approach to study the structure of each PD program as well as the benefits and limitations of PrimeD. Findings revealed that PrimeD offered structure and flexibility that guided leaders to be intentional, notice program improvement opportunities, and embrace collaboration and transparency. The framework holds much promise for integrating a wide array of recommendations for effective PD in the field of integrated STEM PD. Even so, the normal struggles and challenges of a STEM PD will always exist, but can be better navigated through use of a coherent framework such as PrimeD.

Keywords: *framework, in-service, integrated, professional development, STEM education, teacher education*

Introduction

Structuring professional development (PD) experiences with a coherent conceptual framework may improve teacher experiences and increase the likelihood that the PD will change teacher professional practice (Saderholm, Ronau, Rakes, Bush, & Mohr-Schroeder, 2017). The PrimeD framework (original version published in Driskell, Bush, Ronau, Niess, Rakes, & Pugalee, 2016a) was designed to provide such a structure guiding the design and development, implementation, evaluation, and research of mathematics or science PD programs. This study examines the validity of PrimeD as a framework to guide an intervention for three integrated Science, Technology, Engineering, and Mathematics (STEM) PD programs in the United States, focused at different grade bands K-12, through a cross-case synthesis analysis (Yin, 2018). The first four authors of this paper were also each an investigator of one of the three PD programs.

These PD programs employed PrimeD in different ways and to different degrees, making them natural comparisons for assessing the validity of PrimeD as a STEM PD framework. PD 1 was structured by PrimeD from conception to culmination and PD 2 adopted PrimeD in the middle of its first year. PD 3 did not explicitly implement PrimeD, but was designed using many of the same principles that were foundational for PrimeD and used traditional research-informed PD practices. Including PD 3 provides insight into the degree to which using the PrimeD framework provides coherence lacking from the piecemeal adoption of many of the same principles and ideas. All three PD programs followed Moore, Tank, Glancy, Siverling, and Mathis's (2014) definition of STEM as the:

> blending of science, technology, engineering, and mathematics content and context into one learning environment for the purpose of (1) deepening student understanding for each discipline by contextualizing concepts, (2) broadening student understanding of STEM disciplines through exposure to socially and culturally relevant STEM contexts, and (3) increasing interest in STEM disciplines to broaden the pipeline of students entering the STEM fields. (p. 3)

The two research questions for this study were: 1) *How were STEM PD experiences structured in each of the three PD programs?* and 2) *What were the benefits and limitations of PrimeD across STEM PD programs?*

Significance

STEM PD has challenges unique from those normally faced by single-discipline PD. Stakeholders generally have a good sense of the nature and structure of typical science or mathematics PD (e.g., improve content knowledge, instruction). But because the content of STEM PD spans multiple disciplines, problems posed are often ill-defined and solutions are not explicit. Teachers are often asked to integrate STEM disciplines in new ways that go beyond the scope of their preparation and to integrate content areas in which they lack significant preparation (e.g., using an inquiry-based approach) (Brophy, Klein, Portsmore, & Rogers, 2008). Understanding how a framework such as PrimeD can help manage the unique issues of STEM PD offers considerable value.

Background Literature and Conceptual Framework

The PrimeD framework (Figure 1) was initially created from a systematic review of mathematics education and technology literature (Driskell et al., 2016a), then extended from an evaluation of a state-wide mathematics and science PD (Saderholm et al., 2017). As such, it is well situated to serve as a tool to guide STEM PD programs. PrimeD has been applied to multiple ongoing PD programs, both funded and unfunded, with both in-service and pre-service teachers.

STEM PD

Though research on integrated STEM PD is limited, the notion that teachers need PD on the integration of the STEM disciplines is over 20 years old; "[science teachers should] be able to make conceptual connections within and across science disciplines, as well as to mathematics, technology, and other school subjects" (National Research Council, 1996, p. 59). The International Technology Education Association standards state that to achieve true technology literacy, teachers should understand the basic concepts of design and "...comprehend the integrative nature that links technology with science, mathematics, engineering, and other disciplines" (International Technology Education Association, 2003, p. 43).

The National Research Council (2011) describes effective PD in the STEM disciplines as focused on developing teachers' subject-matter content and pedagogical knowledge, addressing the needs teachers face in their classroom context, and providing iterative sustained opportunities for learning over time. Because mathematics has historically been taught in a silo, teachers might only view the integration of mathematics in STEM education as playing a supporting role such as when students compute, create data displays, or use measurement tools (Fitzallen, 2015). Rather, teachers can take advantage of missed mathematics learning opportunities in STEM by using the platform to address specific learning goals (Shaughnessy, 2013) helping students understand that mathematics conceptual understanding is necessary to make sense of science. The lack of content knowledge across STEM fields and teachers' limited design, technology, and engineering knowledge may also cause barriers to implementing STEM education (Hsu, Pruzer, & Cardella, 2010). Implementing STEM education incorporating engineering design requires distinct pedagogical content knowledge for integration of multiple content areas (Brophy et al., 2008).

In addition to content knowledge and pedagogical content knowledge considerations, preparing teachers to implement STEM education requires collaboration with other STEM area teachers and community or industry partners (Bush & Cook, 2016b). Teachers need experiences collaborating across disciplines (Asunda & Mativo, 2015), perhaps through a STEM education professional learning community (as advocated for by the National Commission on Teaching and America's Future, 2010). PD specifically focused on STEM education can provide opportunities for teachers to practice identifying the key science and mathematics content and practices to be taught (Asunda & Mativo, 2015). Such practice is much needed, especially because school districts often only provide teachers with content-specific curriculum maps depicting science and mathematics content in isolation. Teachers want their students to see how the content being learned within and across the STEM disciplines is used in various STEM careers, and would welcome help from education leaders as well as leaders in the STEM industries as they learn about such connections (Leonard Gelfand Center, 2008). The literature is clear that STEM PD presents complex challenges.

The PrimeD Framework Phases

PrimeD draws from key existing frameworks for mathematics and/or science PD (e.g., Guskey, 2000; Loucks-Horsley et al., 2010; Sztajn, 2011). However, PrimeD is unique as it offers a holistic view of PD synthesizing existing PD frameworks into four interconnected, iterative, cyclic phases: Design and Development (Phase I), Implementation (Phase II), Evaluation (Phase III), and Research (Phase IV). Within these four phases are categories, which are later used to organize the results section include (a) common vision and design, (b) outcomes, (c) context, (d) whole group engagement, (e) classroom implementation, (f) evaluation, and (g) research.

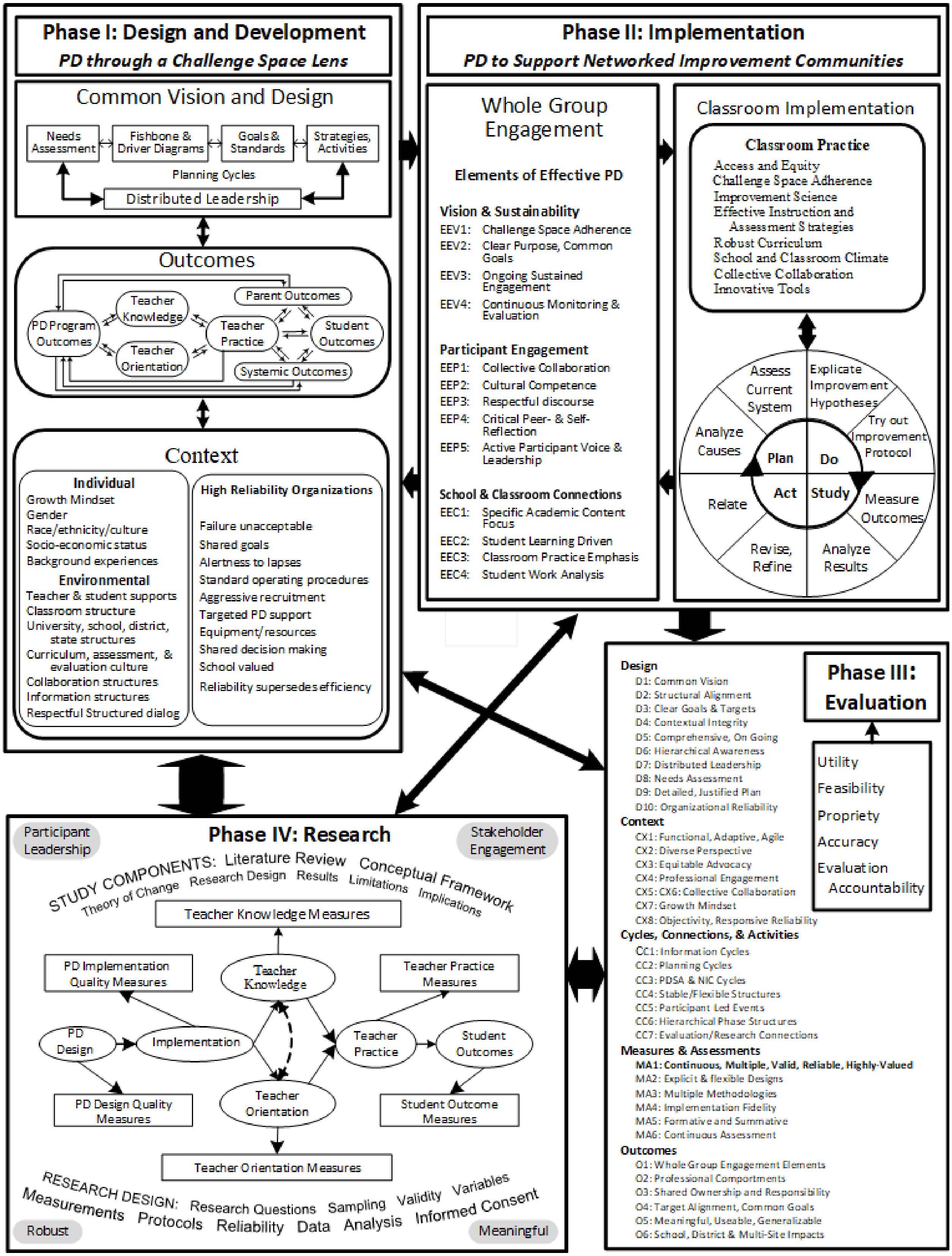

Figure 1. The PrimeD Framework (Revised from Saderholm et al., 2017)

Phase I

Phase I is foundational to every other phase of the PD. This phase calls for all stakeholders (e.g. participants, administrators, designers) to come together to map out a *challenge space*—an explicit description of the needs, vision, goals, targets, and strategies (Bryk, Gomez, & Grunow, 2010). The inclusion of all stakeholders is critical to develop a common vision for the PD program that addresses both school and classroom needs. The challenge space embodies the PD's call to action to improve professional practice and expresses a pragmatic vision for change. A PD session or set of sessions may not address the entire challenge space, but the focus of each session should be purposeful, intentional, and connected.

Phase II

Phase II provides structure to the implementation of the PD program through cycles of whole group engagement and classroom implementation (Figure 1). PrimeD focuses implementation on the development of Networked Improvement Communities (NICs; Bryk et al., 2010; Martin & Gobstein, 2015). NICs are intentionally designed and: (a) focused on a common goal; (b) guided by a deep and consistent understanding of the problem to be addressed with a shared approach to solving it; (c) guided by strategies in improvement research to develop, test, and refine interventions; and (d) organized in ways that accelerate interventions into the classroom.

The PrimeD framework integrates a strong literature base that articulates the characteristics of effective PD (Table 1). The whole group engagement component of Phase II synthesizes extant literature on identified elements of effective PD. The *Elements of Effective PD* in the whole group engagement component represents a synthesis of literature on the structure of effective PD sessions.

For example, Putnam and Borko (2000) noted that teacher learning should be situated within teachers' classroom context, which leads to altering their practice which in turns develops their teaching knowledge and skills (as in Borko, 2004; Lave & Wenger, 1991). PrimeD addresses this recommendation by situating classroom trials as an integral part of the PD. Plan-Do-Study-Act (PDSA) cycles organize classroom implementation in PrimeD helping teachers to focus on continuous improvement and the collection of data to support their conclusions (Bryk et al., 2010; Martin & Gobstein, 2015) as they test change ideas in classrooms. This PDSA process begins as teachers identify a change idea to implement in their classroom. They plan for the implementation of their change idea (plan); implement the change idea in their classroom and reflect on it immediately following the implementation (do); study the effectiveness of the change idea based on data collected during the implementation (study); and then plan next steps (act). This cycle should repeat, both immediately and after collaborating with a school-based team or the whole PD group. The experience and results are continuously shared with colleagues locally (team/school) and globally (entire PD group) to capture input and enhance the learning of the community. PDSA cycles position teachers as leaders and researchers of their own classrooms. This link between whole group engagement and classroom implementation is essential for teachers to realize the ways in which PD sessions connect to their ongoing classroom practice (e.g., Hiebert & Stigler, 2000; Hiebert et al., 2005; Jones & O'Brien, 2014; Philippou et al., 2015; Sabah, Fayez, Alshamrani, & Mansour, 2014; Timperley, 2011).

Table 1

Literature Support for the PrimeD Elements of Effective PD

PrimeD Effective PD Elements	Literature Support
Challenge Space Adherence (EEV1); Clear Purpose, Common Goals (EEV2)	Clear Purpose & Situated in Context: Borko, 2004; Garet, Porter, Desimone, Birman, & Yoon, 2001; Loucks-Horsley et al., 1996; Loucks-Horsley, et al., 2010; Putnam & Borko, 2000; Saderholm et al., 2017; Weiss et al., 1999
Ongoing Sustained Engagement (EEV3)	Sustained Duration: Bush et al., 2018; Desimone & Garet, 2015; Garet et al., 2001; Loucks-Horsley et al., 1996
Continuous Monitoring and Evaluation (EEV4)	Continuous Assessment: Loucks-Horsley et al., 1996; Continuous Improvement: Bryk et al., 2015
Collective Collaboration (EEP1); Cultural Competence (EEP2); Respectful Discourse (EEP3)	Collective Participation: Desimone & Garet, 2015; Loucks-Horsley et al., 1996; Community Based: Bush et al., 2018; Desimone, 2009; Loucks-Horsley et al., 1996; Culturally Responsive: Farmer, Hauk, & Neumann, 2005; Harding-DeKam, 2014; Trumbull & Pacheco, 2005
Critical Peer- and Self-Reflection (EEP4)	Reflect and Revise: Loucks-Horsley et al., 1996; Improvement Science (continuous improvement): Bryk et al., 2015
Active Participant Voice and Leadership (EEP5)	Active Learning: Desimone & Garet, 2015; Leadership Roles: Bush et al., 2018; Loucks-Horsley et al., 1996; Saderholm et al., 2017; Timperley, 2011
Specific Academic Content Focus (EEC1)	Content Focus: Cohen & Hill, 2000; Desimone & Garet 2015; Kennedy, 1998; Loucks-Horsley et al., 1996; Shulman, 1986
Student Learning Driven (EEC2)	Meaningful curriculum and instruction: Bush et al., 2018; Carpenter, Fennema, Peterson, Chiang, & Loef, 1989; Cohen, Raudenbush, and Ball, 2003; Educator Excellence Task Force, 2012; Putnam & Borko, 2000; Verschaffel, Luwel, Torbeyns, & van Dooren, 2009
Classroom Practice Emphasis (EEC3)	Connections to teachers daily teaching: Bush, Cook, Ronau, Rakes, Mohr-Schroeder, & Saderholm, 2018; Cohen, Raudenbush, and Ball, 2003; Desimone, 2009; Educator Excellence Task Force, 2012; Loucks-Horsley et al., 1996; Penuel et al., 2007; Putnam & Borko, 2000
Student Work Analysis (EEC4)	Classroom assessment and reflection: connections to teachers daily teaching: Cook, Bush, Cox, & Edelen, in-press; Gutierez & Kim, 2017; Loucks-Horsley et al., 2010 ; Ng & Tan, 2009; Silver, 1992; Wei, Darling-Hammond, Andree, Richardson, & Orphanos, 2009

Phase III

Phase III is the evaluation of the PD, both formative and summative. Ideally, cyclical ongoing evaluation during Phases I and II provides continuous formative feedback to the PD providers, positioning the evaluator to provide an objective perspective on the design and implementation of the PD. This ongoing relationship between PD providers and evaluators provides a foundation for the summative evaluation at the end of the PD program. Evaluation of Phase I should examine the degree to which the challenge space is identified in a comprehensive and clear way as well as the specification of strategies to be used throughout the PD program that address the challenge space across different PD components. Phase II evaluation should consider the elements of effective PD and connection between classroom implementation and the whole group engagement sessions. Changes in Phase II should flow through Phase I to inform stakeholders and maintain a common vision.

Phase IV

Phase IV (research) is interrelated but distinct from Phase III (evaluation), as outlined by Chyung (2015). The similarities and differences between evaluation and research have been discussed over the last several decades (Glass & Worthen, 1971; LaVelle, 2018; Levin-Rozalis, 2003; Mathison, 2007; Rogers, 2014). Both research and evaluation can employ experimental control upon the participants being studied, but typically research is concerned with the relationships between independent and dependent variables whereas evaluation is mostly focused on whether the treatment worked (Levin-Rozalis, 2003; Mathison, 2007). Research is judged by its accuracy, which is captured by its perceived validity, reliability, and generalizability. Evaluation is also judged by its accuracy, but in addition, on its utility, feasibility, and propriety (Glass & Worthen, 1971; Mathison, 2007; Stufflebeam & Coryn, 2014). Research and evaluation may share the same data and analyses while addressing different goals, roles, and stakeholders. For this purpose, focus on both what worked and why it worked is key to the framework because both evaluation and research are central to the effort.

The center of the Phase IV diagram contains a measurement model that illustrates potential constructs and relationships that a PD study might investigate. Any particular study would unlikely address all of the constructs and relationships shown; typically, researchers using PrimeD would select among constructs and relationships within PrimeD, with justification, making the design process intentional. In addition to functioning as a menu, the diagram may also serve as a map of relationships and constructs further defining the research design.

Methodology and Methods

The present study examines the validity of PrimeD as a guiding structure for STEM PD through a qualitative cross-case synthesis analysis (Yin, 2018) of three PD programs. The two research questions for this study were: 1) *How were STEM PD experiences structured in each of the three PD programs?* and 2) *What were the benefits and limitations of PrimeD across STEM PD programs?* The three PD programs integrated PrimeD in different ways and to different degrees, making them natural comparison points for assessing the validity of PrimeD for improving PD outcomes. All three programs were federally funded, multi-year STEM PD programs. As cases to study PrimeD implementation, PD 1 operationalized the use of PrimeD throughout its entirety, PD 2 employed PrimeD partway through the PD program, and PD 3 did not use PrimeD explicitly. The cross-case synthesis approach supported the aggregation of findings across these programs while considering the holistic features of the cases. As Yin (2018) stated, "the goal is to retain the integrity of the entire case and then compare or synthesize any within-case patterns across the cases" (p. 196).

Tentative conclusions about within-case patterns were first proposed and then replicative relationships were examined across the cases using categories of PrimeD. To guard against threats to validity related to self-fulfilling prophecies (i.e., experimenter expectancies threat to construct validity in Shadish, Cook, & Campbell, 2002), negative cases and alternative hypotheses were an integral part of the analytic process. For example, if the analytic team was inclined to attribute a particular outcome to PrimeD, the situation was examined more deeply to determine whether the PD would have produced the outcome without PrimeD.

Data Sources

A principal investigator or co-principal investigator from each PD program served as the primary source of data. Each of these investigators brought past K-12 teaching experience, years of conducting and leading professional development, and experience as researchers to their respective PD programs. Further, three of the four investigators and the two other authors on this paper were also involved in the development of PrimeD. The investigators from each PD program provided detailed written descriptions of PrimeD implementation in their respective PD along with other program artifacts as supporting evidence (e.g., planning documents, study data, meeting minutes). These persons were also interviewed for clarification about the written descriptions and supporting documentation. Descriptions and conclusions from the analysis were shared with these persons multiple times to verify that the study findings were consistent with their perceptions about their respective programs (i.e., member checks).

Multiple sources of data added validity to the findings (i.e., triangulation; Creswell, 2009). These data sources included videos of whole group PD sessions, document analysis of a variety of program artifacts including, but not limited to, PD planning documents, teacher planning documents, teacher reflections, student work artifacts, reflections of PD providers and project partners, evaluation reports by external evaluation teams, iterative qualitative feedback from external evaluators, and unstructured individual and group conversations. The data collected for each of these cases were collected according to the PD evaluation and research plan for that respective study. In this current study, we examine the existing data across the three cases, including final external evaluation reports, and thus, it was necessary that all three PD programs be completed prior to this study taking place. Including a case that was not guided by PrimeD (PD 3) was essential as it served as a point of comparison (i.e., a qualitative control case). PD 3 was a strong comparison to include as its investigators were well-read and practiced in qualities of effective PD. PD 3 therefore served as a lens to better understand how PrimeD may or may not improve PD outcomes.

Description of the Cases

Case PD 1: Project STEAM. This PD program took place in the Midwest United States and used PrimeD from conception to culmination. The overarching outcome goals of this PD program were to 1) increase students' science and mathematics achievement, 2) increase teachers' and instructional coaches' science and mathematics pedagogical content knowledge, and 3) build a community of educators dedicated to STEAM teaching and learning. In this PD program, five schools from a large urban district participated in the PD program for two years which focused on STEM education with the inclusion of the Arts to engage more learners (giving it the name Project STEAM). The project drew on two research-based STEM education pedagogies: problem-based inquiry, shown to improve urban and minority students' achievement and engagement in mathematics and science (Buck, Cook, Quigley, Eastwood, & Lucas, 2009); and interdisciplinary learning, also shown to enhance learning outcomes and engagement for mathematics and science (Czerniak, 2007). The

STEAM inquiries created and implemented as part of this PD program were set in the context of NGSS grade-level science content and practices.

Participants were 25 teachers in grades three to five (with the exception of one special education teacher and one second grade teacher) and five STEAM instructional coaches (one from each school). Participants were invited by district or building leadership to join the program and served as representatives from their respective schools. Teachers' classroom experience ranged from two to more than 20 years and educational attainment ranged from a bachelor's degree to multiple graduate degrees almost exclusively in education (not in the science or mathematics disciplines). Project STEAM took place from 2015 to 2017 with approximately 35 PD sessions totaling 130 hours which all occurred during the school year. PD sessions mostly took place on the university campus which was a central location for the five elementary schools and were scheduled during the school day from 8:30am – 3:30pm or in the evening from 5:00pm – 8:30pm. The external evaluation team for this program adopted a formative, iterative evaluation process that included PD session and classroom observations, frequent meetings, and summative reports.

Case PD 2: Project INSPIRES. This program took place in the Eastern United States. PrimeD was developed during the first year of project INSPIRES and was not part of the original design of the PD but began being used in the middle of the first year, during participant recruitment. The overarching goals of Project INSPIRES were to 1) characterize teacher attitudes, beliefs, and concerns associated with integrating engineering practices, 2) assess teacher content knowledge and pedagogical skills high school biology and technology education, and 3) correlate teacher knowledge of engineering and pedagogical skill level with student learning. This project provided STEM PD using an educative curriculum (*Introduction to Hemodialysis*) and was guided by the STEM education pedagogy of engineering design which is defined by the NGSS (2013) as including the following three component ideas: defining and delimiting engineering problems, designing solutions to engineering problems, and optimizing the design solution (Appendix I, p. 2).

Project INSPIRES was the third in a series of investigations funded through the National Science Foundation. The first project focused on the development and field testing of five INSPIRES curriculum modules while the second project developed an additional curriculum module and designed, developed, tested and delivered teacher PD programs for implementing an INSPIRES module. All principal investigators of INSPIRES had extensive prior experience conducting and/or evaluating teacher professional development. For example, one investigator led the first two INSPIRES projects. The second investigator co-led the second INSPIRES project and multiple curriculum development and professional development projects prior to INSPIRES. The third investigator had led multiple professional development sessions and participated in the evaluation of the statewide PD that resulted in the development of PrimeD.

The partner district was a large urban district in the Eastern U.S. that had urban, rural, and suburban high schools, all of which were represented in the treatment and control groups. Biology and technology education teachers were invited by district personnel to attend recruitment events, at which the Hemodialysis curriculum and overview of the PD were presented. Teachers signed up to be part of the study either at these events or indicated their interest afterward. Control teachers were recruited separately by district personnel. The treatment group consisted of 38 classroom teachers (22 biology and 16 technology education) across 14 high schools. The control group consisted of 33 classroom teachers (17 biology and 16 technology education) across 15 high schools. Key stakeholders and partners in this PD program included university education and engineering faculty, school district administrators, school district resources teachers, classroom teachers, and the evaluation team.

The project took place from 2014 to 2018 and included an initial year for participant recruitment and psychometric analysis and refinement of measures. The PD program began at the end of the first school year and included three week-long summer workshops and after-school meetings throughout each academic year. All PD sessions took place in the participating high schools. The hemodialysis module targeted all four NGSS (2013) engineering design performance expectations and all eight science and engineering practices. Each year of the PD began with a week-long summer workshop. This first workshop introduced teachers to the hemodialysis unit and provided opportunities for them to engage from the student perspective and to reflect on differences between its approach and their current pedagogy as well as how to implement the unit in their own classes. The second year of PD meetings during the school year focused on examining and reflecting on data from the first year and developing strategies for implementing engineering design in other science units. The third school year focused on implementing those units developed. The external evaluation process was more summative in nature, including mid- and end-year reports and advisory meetings.

Case PD 3: Project STEM PRIDE. This program took place in the Midwest United States. This PD program did not explicitly use PrimeD. The overarching goals of Project STEM PRIDE were to (a) develop middle and high school teachers' understanding and application of STEM education practices, (b) develop middle and high school teachers' integration of STEM education practices into the development of learning experiences, (c) increase middle and high school students' understanding and application of STEM education practices, and (d) increase students' awareness, understanding, and interest in STEM careers. Seven high-needs public school districts from the same state participated in project STEM PRIDE. This program provided STEM PD by experienced PD facilitators focused on the NGSS (2013) and CCSSM (NGA Center & CCSSO 2010) science and engineering and mathematical practices. In addition to integrated and transdisciplinary approaches to STEM education (Honey, Pearson, & Schweingruber, 2014; Krajcik & Sutherland, 2010), this project drew on inquiry (Abd-El-Khalick et al., 2004) and problem-based (Savery, 2015) learning as STEM education pedagogies to frame the approach to whole group engagement and classroom implementation.

Participants included 16 middle and high school classroom teachers and area technology center teachers from 7 high-needs public school districts. Teachers were nominated by district and building leadership. Key stakeholders and partners in this PD program included the 7 school districts, 13 STEM industry partners representing 11 different industries, 10 higher education faculty members in STEM and STEM education disciplines, and the external evaluation team.

This PD program spanned from 2015 to 2017 and included approximately 51 hours of face-to-face PD focused on NGSS (NGSS 2013) and CCSSM (NGA & CCSSO 2010) practices and 80 hours of research internships and industry externships. The PD was unique in that the participating teachers had a research internship in Summer 1 with a STEM content faculty member (40 hours) and an industry externship in Summer 2 with a STEM industry (40 hours) in the same field as their research experience (e.g., health, energy). Teacher participants were expected to develop and implement transdisciplinary, problem- and project-based curriculum. Classroom observation visits occurred during the academic year. The students of the participating teachers (n = 304) took a tour of the STEM content faculty labs on the university campus or the industry partner came out to their classrooms and helped implement the inquiry lessons the teachers had developed. The external evaluation was more summative in nature including mid- and end-year reports and advisory meetings, and classroom visits and observed PD sessions.

Data Analysis

The four point-persons (two for PD 1, one for PD 2, and one for PD 3) worked collaboratively on the data analysis, meeting several times as a group. The two point-persons for PD 1 were the lead principal investigators on the project and the first and third author of this paper. The point-person for PD 2 was a co-principal investigator on the project and the fourth author. The point-person for PD 3 was a co-principal investigator on the project and second author. During group meetings, the four point-persons synthesized data to share individual PD program results organized broadly by the four phases of PrimeD (design and development, implementation, evaluation, and research). To guide the discussions and analysis of the data, *a priori* categories under study came directly from PrimeD and included (a) common vision and design, (b) outcomes, (c) context, (d) whole group engagement, (e) classroom implementation, (f) evaluation, and (g) research. Each PD representative provided the team with detailed summaries and data for their respective PD program, organized by the categories. PD 3 was able to provide information related to all categories, suggesting that the use of PrimeD categories did not bias the analysis in favor of PrimeD. This strategy provided data-informed assertions for each category, drawing from the most relevant data source—or often from multiple data sources within their respective PD program. To better describe how the data sources aligned to the categories under investigation, Table 2 cross-aligns the categories, major themes within each category, and includes example evidence with data sources for each case.

Table 2

Cross-Alignment of Categories, Major Themes, and Example Evidence with Data Sources

Category	Major Themes	PD 1 Example Evidence with Data Sources	PD 2 Example Evidence with Data Sources	PD 3 Example Evidence with Data Sources
Common Vision and Design	Value of teacher buy-in	Teachers not fully informed prior to start of the project (*reflection of PD providers, unstructured conversation with external evaluators*)	Teachers volunteered for project; informed during first year of PD (*PD planning documents and meeting notes; formal interviews by external evaluator; informal interviews with teachers by research team*)	Teachers selected by school district personnel *(needs assessment, unstructured conversation with district leaders, pre-meetings with district personnel)*
	Shared leadership	Identification of mathematics content of focus (*grant application, teacher planning documents, reflections of PD providers*)	District-University partnership to develop PD; teachers included in planning process by end of Year 1 *(PD planning documents and meeting notes)*	Districts shared needs analysis with PD providers, but was news to teachers *(focus group with external evaluators, unstructured conversation with district leadership)*
Targets	Challenge of teacher outcomes	Incompleteness of some written teacher planning documents (*teacher planning documents, reflections of PD providers, external evaluation reports*)	Teachers were excited about the INSPIRES sample module but originally thought that the outcome was to refine it. Resistance to changing pedagogy beyond the INSPIRES module, "traditionalized" some lessons. (*teacher planning documents, observation notes, PD meeting notes, focus group with teachers, external evaluation reports*)	Teachers thought they were getting ready-made material; resistance to creating inquiry-based material *(teacher planning documents, reflections of PD providers, focus group with external evaluators, external evaluation reports)*
Context	Accountability of stakeholders	Lack of administrator awareness of scope of teachers' work (*documented conversations, project newsletter via email*)	Need for administrators to provide common planning time to participant teachers (*informal interviews with teachers*)	Differing curriculum documents and varying classroom expectations *(PD conversations with participants, curriculum documents, focus group with external evaluator)*

	Challenge of data collection	Missing achievement data (*emails, documented conversations*)	Challenges with data collection solved by agreement to audio recording and collection of in-person observation data (*planning team meeting notes and emails*)	Missing completed inquiry projects *(emails, PD conversation with participants)*
Whole Group Engagement	Curriculum development	Published journal articles (*published articles*)	Transfer of pedagogical strategies from INSPIRES module to other lessons (*PD planning documents, PD meeting notes, evaluation of PD activities*)	STEM Inquiry Project *(emails, PD conversation with participants, external evaluation report)*
	Teacher reflections	Depth of teacher reflections (*video recordings of whole group PD sessions, teacher reflection documents*)	Self- and peer-critique on unit planning documents (*PD meeting notes, evaluation of PD activities*)	Depth of reflections in reflective journals *(reflective journals, focus group by external evaluation)*
Classroom Implementation	Connection between PD sessions and classroom implementation	Implementation of PDSA cycles (*teacher completed PDSA templates*)	Implementation of PDSA cycles (*artifacts presented by teachers at PD meetings*)	STEM professional visits to classrooms, student visits to STEM labs on campus *(emails, structured time with teachers and STEM professionals and researchers, reflective journals)*
Evaluation	Connection between evaluation and research	Formative portion of external evaluation (*meeting minutes, documented conversations with external evaluators, external evaluation reports*)	External summative evaluation informed PD design each year. Additional formative evaluation conducted internally (*PD planning documents, meeting notes, external evaluation reports*)	Traditional summative evaluation reports; anecdotal conversations with evaluators at PD sessions *(anecdotal conversations, external evaluation reports)*
Research	Structure and clarity for research	Data collection as key component of study design (*emails, meeting minutes, documented conversations with external evaluators, external evaluation reports*)	Data collection and analysis as key component of project (*meeting notes, data collection administrative documents, external evaluation reports*)	Student achievement data as impact factor for study *(emails, integrated STEM inquiry projects, reflective journal)*

During data analysis meetings, the team conducted a strengths, weaknesses, opportunities, and threats (SWOT) analysis for each of these seven categories across the three cases. The team examined multiple data sources from each project. In doing so, the following questions were considered: In what ways was PrimeD implemented in PDs 1 and 2, and in what ways did the implementation improve or not improve the PD? Did PD 3 experience improvement in the same category without PrimeD as a coherent framework? Why or why not?

Limitations

A key limitation that we acknowledge is selection bias; that is, that the three PD programs analyzed in this study are fundamentally different from other PD programs. The three PD programs identified as cases for this study were all led by STEM PD providers who are also PD researchers whereas many PD programs are district-led initiatives. Second, another potential limitation is the idea that using *a priori* categories runs the risk of failing to analyze other important factors that could have contributed to the effectiveness (or ineffectiveness) of the PD programs under study. However, the purpose of this study was to validate the effectiveness of seven components within the broader four phases of PrimeD, warranting this risk. Third, the use of PrimeD to structure the analysis raises the potential of experimenter expectancy threats to validity given that PrimeD is the intervention under study. Special attention was therefore given to PD 3 and the components of PD 2 not guided explicitly by PrimeD as a means of exploring alternate hypotheses.

Results

This cross-case synthesis examined three STEM PD programs with full, partial, and no implementation of PrimeD as the guiding framework (PD 1, 2, and 3, respectively). The results of the present study are organized by the categories of PrimeD that were analyzed: (a) common vision and design, (b) outcomes, (c) context, (d) whole group engagement, (e) classroom implementation, (f) evaluation, and (g) research. Table 3 provides PrimeD specific component alignment with challenges specific to STEM education PD, synthesized from a review of the literature specific to STEM integration and represents common challenges but is not meant to be exhaustive. Each challenge was given an ID [i.e. INTEGRATION, MATHEMATICS, STANDARDS, ENGINEERING & DESIGN, TECHNOLOGY, INQUIRY, and COLLABORATION] which was used for alignment in the narrative of this section.

Table 3

PrimeD Component Alignment with Challenges Specific to STEM Education PD

Challenge	Description	Supporting Literature	PrimeD Components of Emphasis[a]
INTEGRATION	Learning to integrate disciplines in inquiry-based, conceptual ways	Brophy, Klein, Portsmore, & Rogers, 2008 Estapa & Tank, 2017 International Technology Education Association, 2003	Phase II → Classroom Implementation → Classroom Practice Phase II → Whole Group Engagement → School and Classroom Connections Phase I ↔ Phase II ↔ Phase III PDSA and NIC Cycles
INQUIRY	Learning to implement culturally-relevant contextual STEM education instruction which is inherently open-ended, with multiple solutions, and ill-defined problems which makes it unique to assess	Brophy, Klein, Portsmore, & Rogers, 2008	Phase II → Classroom Implementation → Classroom Practice → Improvement Science Phase II → Classroom Implementation → Classroom Practice → Access and Equity Phase II → Classroom Implementation → Classroom Practice → Collective Collaboration
MATHEMATICS	Integrating mathematics in intentional and meaningful ways rather than mathematics viewed as supporting role/for procedures only	Fitzallen, 2015 Shaughnessy, 2013	Phase II → Whole Group Engagement → School and Classroom Connections → Specific Academic Content Focus Phase I ↔ Phase II ↔ Phase III PDSA and NIC Cycles
STANDARDS	Developing practice to target and identify grade-level standards in authentic STEM inquires while not aligning to too many standards	Asunda & Mativo, 2015 Baker & Galanti, 2017 Cook et al., in-press	Planning Cycles Phase II → Classroom Implementation → Classroom Practice → Robust Curriculum PSDA and NIC Cycles

ENGINEERING & DESIGN	Gaining knowledge and experience with engineering and design practices	Hsu, Pruzer, & Cardella, 2010 Watkins, 2018	Phase I Goals & Standards Planning Cycles PDSA and NIC Cycles
TECHNOLOGY	Addressing limited knowledge, experience, and comfort with technology	Hsu, Pruzer, & Cardella, 2010 Shernoff, Sinha, Bressler, and Ginsburg, 2017	Phase I Teacher & Student Supports, Classroom Structure Phase II → Classroom Implementation → Classroom Practice → Innovative Tools
COLLABORATION	Engaging in the collaborative nature of integrating the STEM disciplines and embracing purposeful collaborations	Asunda & Mativo, 2015 Baker & Galanti, 2017 Bush & Cook, 2016b Honey, Pearson, & Schweingruber, 2014 Moore, Tank, Glancy, Siverling, & Mathis, 2014 Shernoff, Sinha, Bressler, and Ginsburg, 2017	Phase II → Classroom Implementation → Classroom Practice → Collective Collaboration Phase II → Classroom Implementation → Classroom Practice → School and Classroom Climate Phase II → Whole Group Engagement → Participant Engagement → Collective Collaboration PDSA and NIC Cycles

[a] PrimeD evaluation/research connections apply to all challenges.

Common Vision and Design

Two themes were revealed across the three cases with regard to common vision and design. First, stakeholder buy-in was essential. In both PD 1 and PD 3, teachers were selected by district and school level leadership. Though selected because leadership identified them as well-regarded, qualified, and capable to participate in the work of their respective PD programs, some teachers stated that their participation seemed more like a requirement.

Conversely, in PD 2, participation was fully voluntary with recruitment drives held by the university partner, so teachers were initially excited about their participation in the project. In Year 1, prior to PrimeD implementation, teachers became confused about the goals of the project, and some became less enthusiastic while others withdrew from the project. PD 2 found that explicitly tying project outcomes to a needs assessment (in this case implementation of the then newly released NGSS) when communicating with teachers, as well as clear articulation of program goals and discussions that included teachers in the design of PD activities, greatly helped with teacher buy-in [STANDARDS].

In PD 3, a needs assessment was conducted prior to the beginning of the project. Districts were chosen based on their need and desire for innovative STEM curriculum and their identification as a high-needs district, meaning high poverty and low performing such as schools at state-defined assistance levels, or schools exhibiting performance gaps among subpopulations of students. Through the needs analysis, the project leadership team worked with district leaders to identify the schools that would participate in the PD. At the beginning of the project, the leadership team brought together several stakeholder groups (area STEM industry partners, STEM research faculty, and school district leaders) to communicate the vision of the project to all stakeholders and to have a conversation across all stakeholders to ensure a smooth roll out of the project. Round table discussions were facilitated around major STEM areas for which the internships and externships were being organized (i.e., Nutrition, Manufacturing/Engineering, Energy, Healthcare/Medicine, Biology/Environments, Biofuels/Agriculture, Earth Science, and Chemistry). A project leadership team member facilitated the conversation at each table. Industry members and research faculty from the particular topics stayed at the table to give an overview of the work they envisioned doing with the teacher(s), expected outcomes from their work, and possible curricular ideas for K-12 classrooms. School district leaders rotated through each of the tables and were asked to write down names of STEM teachers that came to their mind as good candidates for this PD and to select 2-3 major STEM areas they were interested in having their teachers participate and create curricula around those ideas.

In all three projects, teacher buy-in influenced the degree to which leadership was shared across all stakeholders [COLLABORATION]. In PD 1, evaluators rated the degree of shared leadership that was evident in videos of PD meetings and found that facilitators gradually worked to include more leadership opportunities for teachers. This effort was more effective as teachers and guest speakers bought into the program goals which influenced shared leadership. In PD 2, teachers were brought into a special meeting to discuss, refine, and revise program goals at the beginning of Year 2, after PrimeD was implemented. This special meeting positioned teachers as leaders in the project and improved teacher buy-in. Attrition from the project was reduced, and several teachers who had been thinking of withdrawing from the project decided to remain. Thereafter, teachers presented artifacts from their classrooms at every session and led whole group discussions. In PD 3, teachers were noticeably missing at the stakeholder meeting, but the leadership did not grasp that until after the project began. Teachers were brought into the conversation via the evaluation plan and through more intentional planning of future sessions based on their feedback.

PD 1 found that using PrimeD as a coherent framework enhanced their ability to structure initial discussions of the needs assessment, project goals, and to explicitly create a shared vision. Initial discussions occurred mostly during the grant application stage and the first semester of Year 1 of the project through meetings held at the school district administration office and on the university campus. Attention to PrimeD impelled project leaders to carefully examine the standards chosen, not just list them [STANDARDS]. This examination resulted in the identification of a gap in focus on mathematics standards, which was then addressed in the program design and through working collaboratively with participants and district leaders [COLLABORATION].

In PD 2, teachers were also not part of the initial design decisions. Furthermore, district representatives were consulted but did not help design the program. By the end of Year 1, district and university teams were focusing on disparate yet complementary goals. PrimeD was used explicitly to structure a series of conversations between the two teams toward the end of Year 1, which resulted in a unified set of project goals and strategies. These conversations included the use of Phase I terminology (e.g., "challenge space") and improvement science tools such as fishbone and driver diagrams. Although we acknowledge that these conversations could have been conducted without explicit use of PrimeD, the framework was the structure used to guide them into being more collaborative, which in turn positioned the two teams as partners rather than having primarily one team making decisions for the program [COLLABORATION]. Representatives from both PD 1 and 2 stated that the use of PrimeD to guide discussions about program goals and strategies led the conversations to be less personal or emotionally-charged, leading to greater coherence in the program, as well as collegiality and productivity among project leaders.

The design of PD 3 included several components or partial components of PrimeD Phase I. It included a needs assessment, and distributed leadership with district personnel and industry partners. Teachers, however, were not included as a stakeholder group and had no leadership role in the PD design, a critical feature of PrimeD. This proved to be challenging in the middle of the project when it became clear that the vision of the district personnel and industry partners differed from the vision of the classroom teachers. The sharing of the vision seemed on the surface to be analogous to creating a common vision. The difference, however, lies in whether the already-developed vision is being shared with stakeholders (not fully PrimeD) or the stakeholders are helping to develop the vision (PrimeD). PD 2 demonstrated this difference also because of its first year not being guided by PrimeD. In Year 1, the sharing of the vision with stakeholders was very similar to PD 3: an already-developed vision was given to recipients. PD 2 switched to a more distributed leadership model after Year 1, giving teachers a voice in how the PD activities would occur and allowing dissent and discussion about the desired pedagogical strategies. Only after this switch did teachers in PD 2 begin to embrace the PD goals. In PD 3, only about one-third of participants (two of six teacher teams) fully completed the required program activities, which included developing and implementing an inquiry- and industry-based unit of study.

Outcomes

In PrimeD, outcomes are addressed in all four phases. In Phase I, the common vision and goals, modified by the needs assessment and selected targets and strategies to be used in the PD serve as outcomes. In Phase II, formative assessments of outcomes are used as foundations for whole group discussions and classroom implementation strategy refinement. In Phase III, the focus is on measuring the degree to which outcomes have been reached, and in Phase IV, factors influencing how or why outcomes were or were not reached are examined. The present study focuses on the outcome of transforming teachers' practice from a traditional to an inquiry mode of instruction [INQUIRY]. This outcome is related to the common vision and design in that changing pedagogical approaches to teaching was a key goal for all three PDs.

PD 2 exhibits how conversations with teachers regarding this outcome, and their subsequent positionality toward teaching in an inquiry approach, changed in conjunction with the implementation of PrimeD as the guiding framework. Teachers in PD 2 stated in surveys and focus groups that they were excited about integrating the inquiry-based hemodialysis module into their curriculum. During Year 1, the study found that teachers were, however, "traditionalizing" some of the key lessons in the module, removing the inquiry basis and instead providing lecture notes prior to the beginning of any activities [INQUIRY]. At the beginning of Year 2, now using PrimeD as the guiding framework for a discussion about the PD, the facilitators opened the conceptual space of the PD to teachers by discussing the phenomenon of traditionalizing lessons with the teachers and including them in decisions about how to address the common goal. The teachers contested the notion that any approach other than lecture followed by a confirmatory activity might improve student outcomes, so Summer 2 PD was redesigned to engage teachers in studying research, recommendations by the National Research Council, and comparing/contrasting lessons conducted through traditional vs. inquiry lenses. Teachers voiced discomfort with the program's attempts to change their teaching practice and were much more comfortable with the notion of adding interesting activities into their existing pedagogical strategies (based on surveys, classroom observation measures, whole group meetings, focus groups). But by the end of Year 2, many teachers began demonstrating an ability and a willingness to design and deliver inquiry-based lessons. The improvement in Year 2 only happened after a concerted effort to adjust the challenge space to include teacher voice, i.e. their reticence to shift their pedagogy. Year 3 PD strategies were revised to include one-on-one and small group consultation on teacher-developed lessons.

Similarly, in PD 3 teachers wanted to "organically" take new content ideas and questioning strategies and incorporate them into their existing curriculum rather than create new curricula centered on STEM PD program outcomes [MATHEMATICS, ENGINEERING & DESIGN, TECHNOLOGY]. External evaluators held focus groups with the leadership team and the participants during each whole group engagement session. If there were major concerns aired in the whole group meetings with participants, leaders were made aware of it, but other than that, they were not shown any results until the yearly reports. With PrimeD, PD 1 held more interactive conversations with evaluators and participants, which helped brainstorm ideas and shift PD strategies as needed. Such discussions were not held in PD 3. Although such discussions could be held without PrimeD, PD 3 exhibited a fairly traditional evaluation and communication structure that positions teachers as recipients, and PD 2 did not have the discussions until PrimeD became the guiding framework.

PD 1 found similar results to PD 2, but earlier in the program, coinciding with its use of PrimeD as the guiding framework from the outset [INTEGRATION, MATHEMATICS, INQUIRY]. Teachers in PD 1 reported more perceived benefits of altering their practice in whole group meetings and began to identify individual areas for growth (e.g., selecting a change idea) through the implementation of the PDSA cycles in the first year of the program (see Phase I narrative). As the PD program progressed, facilitators also observed teachers showing more willingness to consider changing their pedagogical approaches [INTEGRATION, INQUIRY]. The increased willingness to embrace new pedagogical approaches can be directly tied to the explicit use of PrimeD. The PDSA cycles provided concrete activities to take PD ideas into the classroom. PDSA by itself is not necessarily evidence of the effectiveness of PrimeD because PDSA is part of improvement science, which is more general than PrimeD (Bryk et al., 2010). The connection between PDSA and whole group activities made explicit in PrimeD helped lead to the improvement seen in PD 1. Specifically, teachers "tried out" a change strategy in their classroom, then brought the results back to the whole group for discussion and refinement. Through multiple iterative cycles, an integral component of PrimeD Phase II, teachers gradually embraced the new pedagogical strategies and approaches.

Context

PrimeD identifies a wide array of contexts but the present study focuses on school and district-level environmental contexts. In PD 1, building administrators were supportive of the teacher participants in their buildings, but were often unaware of their accomplishments in the PD (informal interviews, discussions). PrimeD specifically considers the viewpoints of all stakeholders and considers obstacles as challenges to be addressed in the challenge space. PD leaders therefore discussed the issue and created a PD newsletter to maintain a line of information and communication to administrators [COLLABORATION]. In PD 2, administrators were generally supportive of teacher participation, but teachers reported in several schools that more targeted supports were needed such as common planning time. Teachers communicated this in Year 2 after the implementation of PrimeD and noted that this issue had been a struggle for them in Year 1 but that they had not felt that they had a clear avenue to communicate the issue. PD leaders therefore focused on helping teachers within and between schools collaborate more easily (e.g., shared drives, social media groups, teacher-led planning and presentation sessions above and beyond planned PD meetings).

PD 3 also struggled with school contexts, most noticeably with regard to the involvement of guidance counselors. In the original design, the PD planned to include a guidance counselor from each participating school as a co-participant with the teachers [COLLABORATION]. Only a single guidance counselor was a participant by the end of the first year. The absence of guidance counselors was never fully addressed, so that aspect of the PD design was abandoned.

Although addressing contextual issues clearly can occur without PrimeD in a PD, the positioning of teachers as leaders and prompting teachers to discuss the structure of the PD did not occur in PD 2 until PrimeD was adopted as the guiding structure. In PD 1, in which PrimeD was the guiding structure from the outset, the communication structure was established specifically to gather input from all stakeholders, and the need for better communication was identified very early in the project. In PD 3, in which PrimeD was never adopted as a guiding framework, the contextual issues were known but never addressed.

Whole Group Engagement

PrimeD calls for participants to have a leadership role in the PD, not merely receive information. In all three PD programs, teachers created STEM education curriculum materials (in the form of lesson plans, unit plans, inquiries, curriculum maps, etc.) [INTEGRATION, MATHEMATICS, ENGINEERING & DESIGN, TECHNOLOGY, INQUIRY, COLLABORATION]. In PD 1, the curriculum development piece was successful, with some teachers even disseminating STEM education problem-based inquiries they developed to key practitioner journals in science and mathematics education. All teachers fully engaged in the reflection component of the curriculum development process but were less willing to critique their peers (*critical peer reflection* in PrimeD). The use of PrimeD as the guiding framework led the PD evaluator to identify this gap early in the project, and the PD was redesigned to engage participants in activities to reduce discomfort around peer critique (e.g., identifying pitfalls and best practices for peer critique).

In PD 2, the goal of creating STEM lessons was unclear in Year 1. In Year 2, the implementation of PrimeD led to discussions, in which this particular goal was clarified. After some tense conversations, teachers supported a primary goal of taking STEM education instructional strategies learned from the hemodialysis unit and incorporating these strategies into their other instructional units [INTEGRATION, ENGINEERING & DESIGN, INQUIRY]. Furthermore, teachers pointed out that time and support had not been sufficiently allotted in the original PD design to support this goal. The PD for Year 2 was therefore restructured to provide focus on identified content areas of growth in the morning (e.g., engineering design principles) and the afternoon was dedicated to teachers developing lessons in small groups, with each group creating two inquiry-based engineering design lessons [MATHEMATICS, ENGINEERING & DESIGN, INQUIRY, COLLABORATION]. Teachers in PD 2 owned the curriculum development portion of the program because they were the ones that drove and pushed for it, and they became effective at critiquing each other and increasing the quality of the instructional units, as evidenced by PD meeting notes and informal discussions with teachers. By the end of Year 2, surveys indicated that teachers had come to most value this part of the PD.

In PD 3, teachers were not invested in the curriculum development portion of the PD. Several teachers attended all PD sessions except the ones in which curriculum development was scheduled [INTEGRATION, MATHEMATICS, STANDARDS, ENGINEERING & DESIGN, TECHNOLOGY, INQUIRY]. Though curriculum development was a key component of the PD and participants were aware of this from the beginning, participants revealed in surveys, whole group discussions, and informal interviews that they were more interested in implementing 'ready-made' curricular materials. Project leaders in PD 3 did not have a formally-defined challenge space and struggled to identify curriculum development resistance as a challenge to be addressed as part of the PD instead of an insurmountable obstacle. Although this issue could be addressed without PrimeD as the guiding framework, PrimeD includes targeted information and communication cycles for the specific purpose of redefining the challenge space and improving whole group engagement.

Classroom Implementation

Upon analysis, we found that PrimeD made a great impact on the implementation component. In PDs 1 and 2, the expectation to incorporate iterative PDSA cycles was clear and provided a seamless connection between whole group engagement and classroom implementation. For both PD programs, teachers completed the PDSA cycles individually and in collaboration with other participant teachers in their buildings [COLLABORATION]. Teachers returned to whole group meetings with artifacts from their implementation, including video recording, student work samples, lesson plans, and PDSA reflections. The PDSA cycles positioned classroom implementation as a central component of the PD. Teachers developed agency to direct their own improvement efforts and view their classroom practice through a research lens. This positionality led them to view themselves as leaders in the PD.

In PD 3, classroom implementation was positioned as a result of the PD, not an integral component that drove the PD. For example, teachers were asked for anecdotal examples of how they were implementing focus practices [INQUIRY], but no formal evidence was collected. In Year 1, teachers were not provided a standard template for them to follow in terms of creating the instructional sequence, and the lack of clarity became a barrier to classroom implementation. In Year 2, a template was provided, and teacher participants were more successful in the creation of their instructional sequences. In addition to the instructional sequence as an artifact, student work samples were collected to show impact (or not) of their instructional sequence. PD 3 leaders were caught off guard by the lack of participant commitment to creating instructional sequences when they began to emphasize it in the PD meetings. PD 3 demonstrates that even without PrimeD as a framework, varying levels of communication will naturally identify barriers, and the PD design can be adjusted to better address the needs. PrimeD, however, creates formal information and communication cycles for identifying emergent challenges—barriers are viewed as an expected and normal component of meaningful PD. In PD 3, the classroom experiences were never explicitly structured or positioned as part of a feedback cycle to drive whole group activities, a key feature of PrimeD.

Evaluation

PD 1 benefited from a process through which evaluators provided formative feedback throughout the project. An evaluator was present at PD planning meetings, and PD leaders had in-depth conversations with the evaluation team more than once a month [COLLABORATION]. PD 1 leaders left these conversations with new plans, course corrections, and a to-do list with the focus often on more effectively meeting the needs of teacher participants as they embarked on STEM education instruction.

In both PDs 2 and 3, evaluation was designed to follow a more traditional external, summative approach (e.g., mid-year and end-of-year reports, yearly advisory board meetings). In PD 3, evaluators conducted classroom visits, attended every whole group engagement session, and held focus groups with the leadership team and participants at each session. If there were major concerns aired by participants, the leadership team was informed. But beyond that, no results or feedback were given until yearly reports. In PD 2, the adoption of PrimeD led PD leaders to recognize a need for more frequent formative assessment during the development of the challenge space, so they augmented their internal formative evaluation. This internal evaluation process led PD leaders to view feedback from district personnel and participants more dispassionately and to filter criticism back through the challenge space.

Having the evaluation component visually represented in PrimeD was a key benefit for both PD 1 and 2. This structure helped to facilitate in-depth conversations with key stakeholders. Importantly, being able to point to the framework when discussing the challenge space shifted conversations away from personal opinions, qualities, or performances, thereby lowering tensions and making conversations more objective and focused on solutions.

Research

Viewing research as an integral component of PD adds access, richness and complexity to the process. PrimeD recognizes that teachers conduct research as a normal function of their practice; that is, they test and evaluate their approach to teaching every day. Although valuable and critical for teachers to develop successful strategies, these types of efforts are often contextually limited. PrimeD offers a structure that can make these normal research activities robust and meaningful for a larger audience by connecting Phase II and Phase IV activities. PrimeD supports the building of strong, meaningful partnerships between teachers and researchers to further study how research impacts classrooms directly and thus increases the ability for such efforts to enhance the knowledge of the field. Stenhouse (1989) argued that not only should teacher's work be studied, but it should be studied by the teachers themselves. Teacher research as a form of PD has been shown to boost teachers' self-esteem and confidence, help them become more flexible and proactive, and grounds them with realistic expectations (Atay, 2008; Chow et al., 2015; Clark et al., 1996; Elliot, 1990, 1991).

In PD 1, district leaders and participants appeared to view research, particularly quantitative data collection, as being separate from the ongoing objectives of the PD, but district leaders did provide support from the district's research office to ensure data required for the grant was obtained. The use of PrimeD helped to prompt some discussion about the connections between research, design, and implementation with district leaders and participants, but some still seemed to view research as an add-on to leaders and teachers already full plates.

In PD 2, district leaders and participants viewed the research as being separate from the PD and its objectives. District leaders did not see themselves as partners in the research on the PD and provided only limited support for that aspect of the program. New district regulations blocked the collection of required data (especially video recordings of lessons) at the end of the first year. The district eventually agreed to audio recording and in-person observations as a compromise.

In PD 3, participants also viewed research on PD as separate from the PD. As described earlier, participants were less willing to participate in the classroom implementation components, which increased the difficulty of obtaining classroom data. This view of research as separate led to large attrition between pre- and post-measures, potentially compromising the validity of the research findings.

Discussion and Conclusions

The present study examined three PD programs to compare their uses of PrimeD, which integrates recommendations for effective PD from multiple sources (e.g., Borko, 2004; Desimone, 2009; Greeno et al., 1996; Guskey, 2000; Lave & Wenger, 1991; Loucks-Horsley et al., 2010; McAleer, 2008; Penuel et al., 2007; Putnam & Borko, 2000; Sztajn, 2011; Timperley, 2011). Any individual component of PrimeD can therefore be potentially attributed to the use of relevant theory and this study therefore focused on the use of PrimeD as a coherent framework rather than individual components of PrimeD. PD 3 provided a control case in which much of the relevant theory that is incorporated into PrimeD was considered in the PD design. Similarly, PD 2 adopted PrimeD as a coherent framework at the end of its first year, with many components of PrimeD having been considered prior to its adoption as the guiding structure.

The study found that PrimeD provides a systematic tool for navigating a STEM PD program. In several categories, the benefits afforded to PD 1 and PD 2 that were attributed to PrimeD could potentially be reached without PrimeD. This admission is balanced, however, by the fact that the adoption of PrimeD in PD 2 or explicit referral to the PrimeD model in PD 1 identified gaps in the way leaders had been thinking about various aspects of the PD (e.g., distributed leadership). Furthermore, PD 3 leaders were well-versed in effective PD literature, but they did not synthesize that literature to address various challenges as well as PDs 1 and 2 (e.g., teacher buy-in). PrimeD helped project leaders to be intentional, to not miss opportunities to improve, to formatively evaluate and make course corrections, and to be transparent and collaborative. We concluded that the normal and expected struggles and challenges of a STEM PD will routinely exist, but can be better navigated through the use of a coherent framework such as PrimeD.

The cross-case synthesis analysis revealed two themes regarding common vision and design. First, the PrimeD approach to creating a common vision with all stakeholders is different than sharing an already-developed vision with stakeholders. Second, the PrimeD approach requires a distribution of leadership to include teachers in the decision-making process, both in the initial design and throughout the PD program. PDs 2 and 3 demonstrated that excluding teachers resulted in a top-down approach to PD that limited teacher buy-in. Taken together, the three PDs demonstrated that the more teachers are included in leading the project, the more they will buy into the goals of the PD and work toward achieving those goals.

Challenges that Remained Regardless of PrimeD

A limitation of PrimeD is that while it serves as a road map, it does not include strategies or "how-to's" for addressing the different components. All representatives of PDs 1 and 2 agreed that having suggested strategies for how to best address roadblocks faced within current components of PrimeD would have been beneficial. PD programs are subject to unique challenges specific to local context and needs. The development of tools and strategies is a suggested area of future work.

Research as PD (Phase II in PrimeD) was not well defined. As a result, none of the three PD programs were highly successful in integrating research as a seamless part of their program. All three PD programs included robust research designs, and all three encountered similar difficulties with district, school, and teacher buy-in. Even when accepted as a component of the program, teachers and district leaders saw the research as separate from the PD. This study identifies the need for a clearer delineation of the role of research in the quality of the PD and strategies for helping participants and other stakeholders embrace research as a normal component of their PD practice.

Benefits of PrimeD

PDs 1 and 2 benefited most from PrimeD when they used it as a checks-and-balances tool to ensure the comprehensiveness and alignment of the different PD components, which in turn helped teachers receive a well-designed, intentional STEM education experience focused on addressing the challenges. The explicit use of PrimeD as a coherent framework significantly facilitated PDs 1 and 2 leader communication, enabling them to navigate conversations with different stakeholders in ways that remained objective and focused on program goals. Additionally, PrimeD helped focused appropriate attention on classroom implementation, placing it and whole group engagement as equal partners on a teacher's professional journey, which is a key component of the COLLABORATION STEM PD challenge, as outlined in Table 1.

Conclusions

This study found that PrimeD had a positive impact on all program components to the degree that it was operationalized as a coherent framework to guide all aspects of the PD. The framework holds much promise for integrating a wide array of recommendations for effective PD in the field of STEM PD. The framework synthesizes these recommendations and provides a roadmap for PD leaders to design, implement, evaluate, and research PD that has a lasting impact on classroom practice and student outcomes.

Sarah B. Bush (Sarah.Bush@ucf.edu) is an Associate Professor of K-12 STEM Education at the University of Central Florida. Her research and scholarship focuses on deepening student and teacher understanding of mathematics through transdisciplinary STE(A)M instruction. She is a member of the board of directors of the National Council of Teachers of Mathematics.

Margaret J. Mohr-Schroeder's (m.mohr@uky.edu) research interests include investigating ways to broaden participation in STEM, especially of underrepresented populations and the effects these mechanisms have on their STEM literacy. Through this work, she has focused on creating opportunity and access to STEM experiences for each and every participant.

Kristin Cook (kcook@bellarmine.edu) is an Associate Professor of Science Education at Bellarmine University in Louisville, KY. A former high school biology teacher, Dr. Cook has served as a professional developer and consultant for elementary, middle, and high school STEAM-focused school reform. Dr. Cook's research focuses on engaging students and teachers with the community of science through transdisciplinary STEAM instruction.

Christopher R. Rakes (rakes@umbc.edu) is an Associate Professor of Mathematics Education at the University of Maryland Baltimore County. He studies the use of technology for teaching mathematics, mathematics misconceptions, and professional development of mathematics and science teachers.

Robert N. Ronau (bob@louisville.edu) served as a faculty member at the College of Education and Human Development at the University of Louisville for 27 years and nine years as the Associate Dean for Research. In the later capacity he oversaw grant funding, graduate studies, doctoral programs, and technology for the college. Dr. Ronau currently serves as a senior advisor in the EDD program at Johns Hopkins University.

Jon Saderholm (saderholmj@berea.edu) is an Associate Professor of Education Studies at Berea College. He also directs the Yahng Discovery Center, which is a STEM outreach center at Berea. He taught science and mathematics for 17 years and earned a National Board for Professional Teaching Standards (NBPTS) certification in high school science before leaving the profession to pursue graduate studies.

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