Modeling Authentic STEM Research: A Systems Thinking Perspective[i]

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Most inservice teachers have never experienced the practices of science and engineering research first hand or have had only limited exposure. The style of teaching with which they are most familiar is the typical transmission style lecture with occasional cookbook verification laboratory exercises, a common feature of large section undergraduate science and engineering courses. In addition, the often held perception that doing science is simply the "Scientific Method" as espoused in major textbooks results in an over simplification of the nature of research that it is a static, linear process (Windschitl, Thompson, & Braatan, 2008) and distracts teachers and students from "productive inquiry" (Tang, Coffey, Elby & Levin, 2009). The Next Generation Science Standards (NGSS) advocates for a learning progression orientation for developing student understanding of cross cutting concepts and the discourse and practices that embody the research process. Students are expected to acquire understanding of elements of the nature of science through engagement in classroom activities that incorporate these concepts and research practices. Duschl, Bismack, Greeno, and Gitomer (this volume) present strong arguments for the potential of the NGSS approach for enhancing K-12 science learning, and the ability of K-12 students to successfully engage in this type of learning. However, for this to happen teachers must incorporate the discourse and practices of science and engineering into their science teaching (NRC, 2007, 2012, 2013). This expectation poses a major challenge for many K-12 inservice teachers. If teachers who have only minimal experience doing research are expected to incorporate the discourse and practices of science and engineering into their teaching, then professional development programs are needed to provide depth of understanding of the research enterprise and how to translate that understanding into classroom teaching, either by implementing existing curriculum, or by designing original lessons.

This chapter presents a teacher professional development model that focuses on understanding how scientists and engineers do research and on helping teachers translate that understanding into the classroom. The chapter begins with a description of the Center for Science and the Schools (CSATS) at Penn State and of the teacher-researcher partnership PD programs provided by CSATS. Second, is a section about the PD model, including how it was developed, a description of the systems-based framework and the dynamic research processes it represents. This is followed by how CSATS has been using various aspects of the model in its PD programs involving teachers and STEM graduate students and by reactions of teachers and STEM graduate students and faculty to its use. Finally, a discussion of implications and next steps is provided regarding plans for research on using the model with teachers, graduate students and faculty.

CSATS at Penn State

The challenge of building capacity for teachers to teach in ways set out by NGSS has been at the forefront of CSATS efforts (csats.psu.edu). CSATS is a STEM education outreach center whose mission is to build mutually beneficial and sustainable relationships between Penn State STEM faculty and K-12 schools to enhance STEM education in PA and nationally. Our professional development (PD) programs have arisen primarily through researcher initiated STEM education grants or broader impacts components of science/engineering research grants. In all of our programs, CSATS personnel work closely with university STEM researchers, including graduate students, to collaboratively develop teacher PD programs that are grounded in faculty members' research areas, connect to K-12 academic standards, model inquiry-based teaching practices and incorporate best practices for teacher PD. Each PD program is unique in terms of its format, STEM discipline area(s), and degree of direct involvement in an authentic research project. "Authentic research" here is defined as research conducted by STEM faculty which may be supported by internal or external grant funding. Alternatively, "classroom research" refers to coordinated classroom activities that mimic authentic research in design, and which investigate a phenomenon for which there is no particular known answer. Characteristics of the CSATS PD programs are summarized in Table 1.

Table 1. CSATS Teacher Professional Development Programs and Characteristics (TRE = Teacher Research Experience; AY = academic year; GS = graduate student)

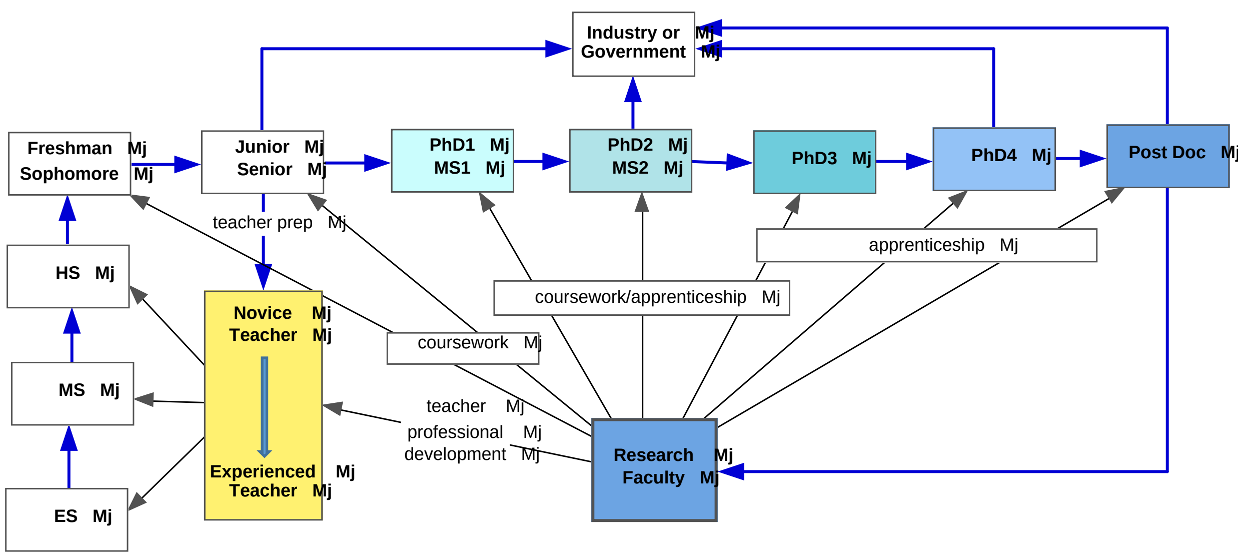
Structure	**Characteristics**
AY GS-Teacher partnerships	• Targeted partner school districts; middle and upper elementary school teachers • Varied topics related to teachers' curriculum and grad students' research and content expertise • Weekly PD for graduate students on communication and elements of inquiry-based teaching • Ongoing academic year program involving partnerships between graduate students & teachers • Collaborative design and co-teaching of standards relevant classroom lessons and research projects
Summer TREs and AY workshop series	• Targeted partner school districts; middle and high school teachers • Topics related to nanotechnology, energy sustainability and health monitoring • 6-week summer TREs co-mentored by grad students; weekly half-day PD workshops • 3-4 academic year one-day PD workshops for all district science teachers • Support for teacher implementation of classroom inquiry-based activities • Faculty and graduate student presentations of individual research projects • PD for graduate students on communication with non-technical audiences and elements of inquiry-based teaching
AY workshop series	• Targeted partner school district; elementary, middle and high school teachers • Topics linking environmental disruption and disease outbreak • Ongoing academic year workshops with K-12 teachers teaching a variety of disciplines • Faculty and graduate student presentations about aspects of the ongoing research project • Instruction on procedures and techniques used in research project • Support implementing classroom activities and research projects paralleling authentic research
5-day Summer workshops	• Random school districts; middle and high school teachers • Topics related to engineering systems, bioenergy and biofuels • 5-day summer workshop with sessions focusing on various components of the project • Faculty and graduate student presentations and instruction on procedures and techniques used in the research project • Preparation for researchers in communication and aspects of inquiry-based teaching
AY one-day episodic workshops	• Random school districts across PA; K-8 or 7-12 teachers • Academic year one-day workshops; Different research project for each workshop • Focus on standards relevant topics related to researchers' areas of research • Faculty and graduate student instruction and engagement of teachers in inquiry-based activities • Preparation for researchers in inquiry-based teaching methods and design of inquiry-based lessons

A growing focus of CSATS is to optimize teacher learning through teacher-researcher partnerships by devising strategies that allow teachers to (1) examine the dynamic nature of authentic science and engineering research and (2) translate this understanding into their teaching. Since our PD programs have inherent connections with researchers' projects, we use the PD as a context for examining practices of science or engineering research and as a springboard for engaging teachers in the use of these practices when implementing classroom research projects. As can be seen in Table 1, graduate students play important roles acting as workshop instructors, as co-mentors for teachers during summer Teacher Research Experiences (TRE), and as coaches or co-teachers for classroom activities and research projects. However, the graduate students also vary in their own breadth and depth of research experience. In order to enhance CSATS's PD efforts, we developed the Modeling Authentic Science, Technology and Engineering Research (MASTER) Model which is designed to capture the dynamic, systems nature of authentic research to help make that accessible to novice researchers.

Designing the MASTER Model

Although the approach for the design of the MASTER Model (henceforth M-model) considered observations and findings from multiple sources, here two are highlighted. The first source involved working with science and engineering faculty to prepare research grant proposals, and for those that were funded, learning about the progress of that research over the life of the grant. Analysis of the structure of 25 federal research proposals (e.g., National Science Foundation, National Aeronautics and Space Administration, US Department of Agriculture) spanning numerous STEM fields and observations during engagement in the projects revealed a recursive pattern that can be represented in terms of a dynamic, complex system of interrelated and interdependent components, subcomponents, and depending on the complexity of the research design, sub-subcomponents. Each component and subcomponent is guided by research questions or goals, underlying sub-questions or sub-goals, ultimately to the point of the individual experiments or tasks. At the heart of the research design is the expectation that ongoing findings from the seemingly separate parts are regularly communicated across the project to inform ongoing progress, allowing next steps as planned, or requiring changes. Through this communication process, the system evolves over the course of the research project. Thus the M-model includes both a framework depicting the research design at any one point in time, and the dynamic processes that shape and mold the framework over the time of the research project. The M-model combines and applies the cross cutting concepts of systems thinking and model-based reasoning to promote understanding of how researchers do research.

Also informing the M-model design and its use at Penn State are personal observations and reports in the literature about how undergraduate and graduate students become independent researchers. Figure 1 presents a flow diagram depicting a typical undergraduate and graduate student progression observed for STEM majors at Penn State. Future science teachers and future researchers share similar early preparation as undergraduate STEM majors, e.g., coursework taught via traditional dissemination style lecture with associated laboratory exercises. By their nature, these early experiences reinforce the simplistic perception of research as the "scientific method," and the separation of research and knowledge building. Such experiences also tend to isolate students from the larger overarching research system and thus prevent them from seeing interconnections among subcomponents. In addition, many research skills are needed by science teachers in order to support student learning via inquiry-based methods. For example, in a study of five pre-service high school teachers engaged in a one-year field experience, Crawford (2007) found that these preservice students struggled with "framing questions, grappling with data, creating explanations, and critiquing explanations (including others' explanations in a public forum), …important components associated with teaching science as inquiry" (p. 637). However opportunities to develop these skills are limited in undergraduate education. In a study aimed at understanding how researchers learn to do research, Feldman, Divoll and Rogan-Klyvev (2009) examined research proficiencies of honors undergraduate, Master's, and Ph.D. students working on an interdisciplinary research project involving numerous research faculty. Feldman et al. describe methodological and intellectual proficiencies that emerged from the study, and timing associated with appearance of these proficiencies across student levels. They found that advanced methodological proficiencies, such as data analysis and ability to report findings to other researchers and defend them based on data were not evident until early in graduate studies. Intellectual proficiencies associated with research such as designing research questions based on the literature, framing hypotheses, situating individual's research within the context of the broader research space of the lab or the literature, and contributing to the broader knowledge base were not evident until the later stages of Ph.D. programs. This lack of exposure contributes to teachers' limited skills in aspects of research they are expected to help develop in their students. In response to these observations and findings, the M-model not only represents the systems nature of research, but also provides opportunities for highlighting methodological and intellectual skills involved in the research process.



Description of the MASTER Model

The M-model consists of a multiple-level systems-based Framework and the dynamic processes therein. Figure 2 provides a generalized representation of the Framework's overall research system subdivided into several interconnected and interdependent recursive units. Black lines represent relationships among subcomponents and components to the overarching research plan; gray arrows represent possible interrelationships and interdependencies among components and subcomponents. The boundaries of the system may vary, depending on the scope of the research as well as the purpose and context in which the research is done. As such, the Framework can represent an entire inter-institutional, multidisciplinary project whose work involves numerous research labs, an individual research faculty's funded research project, and/or the work of an individual graduate student focusing on one piece of the overall project.

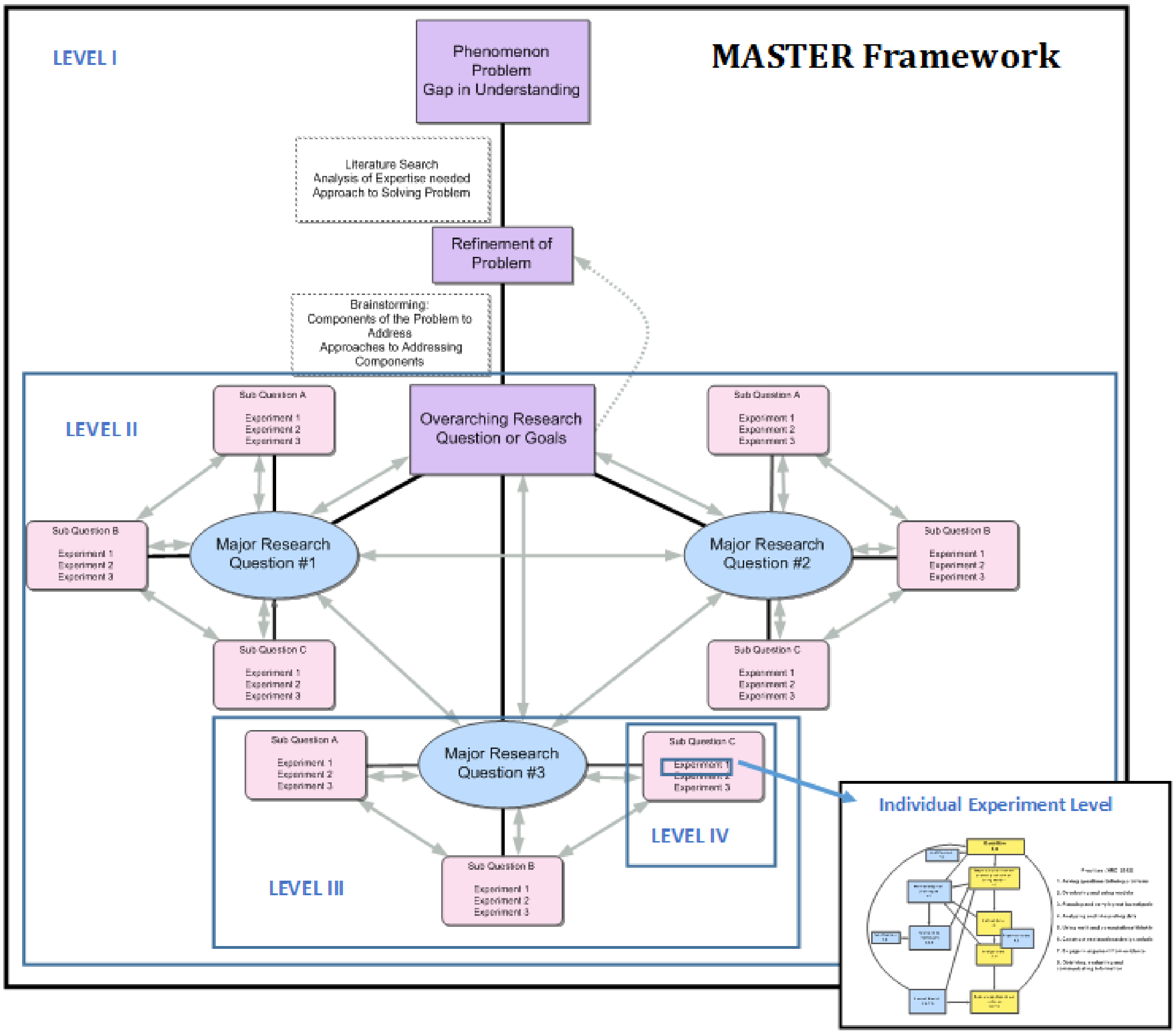


Figure 2. Template for the MASTER Model Framework

Level I of the M-model Framework presents the complete planned research project and is intended to capture the development phases of the overall research or engineering design plan. At the initial planning stage, researchers identify a phenomenon or design problem and conduct literature reviews to develop a rationale and identify gaps in knowledge related to the problem. If the idea continues to be viable, the problem is refined to a focused and testable overarching research question or design problem. The next step is development of a research design to address the overarching question or design problem. The plan is comprised of several recursive units, each addressing a different guiding question that represents a different facet of the overarching research question/design problem. Each recursive unit, in turn, is made up of several subcomponents, which may have sub-subcomponents, too. The smallest element in the Framework is the individual experiment, several of which may be needed to address the sub-component at hand.

Level II of the system provides a bird's eye view of the entire research process as it unfolds, including interconnections and interdependencies among all elements of the research system (gray arrows). **Levels III and IV** sequentially narrow the boundaries of the system within each recursive unit to consider individual components and subcomponents of the research design. Depending on the scope of the research project there may be additional levels involved. The finest grained level of focus is the **Individual Experiment**. It is here that measurements are taken, data is obtained, analysis of the data occurs, and patterns of evidence for supporting future claims are generated. As the project progresses, the research design will adapt and evolve due to changes made in procedures and strategies because of new information gained from experiments and analyses of information at the various levels.

Although considered separately in the Framework, in practice, these recursive units are interconnected and interdependent across any of the levels. When combined, the findings contribute to solving the overarching problem. In the Framework template, all of the arrows are bi-directional and weighted the same. However, when depicting an actual project, they could be used to indicate directions of information flow, and weighted to indicate the extent of the interdependency. The need and opportunity for change arises by virtue of communication within and across components and subcomponents comprising the system. Also, the levels of the Framework are described here in numerical order in terms of their hierarchical position within the recursive unit, reflecting how they were derived during the planning stage. However, once the initial research plan is in place and implementation begins, the sequence becomes reversed and eventually interwoven, as shown in Figure 3.

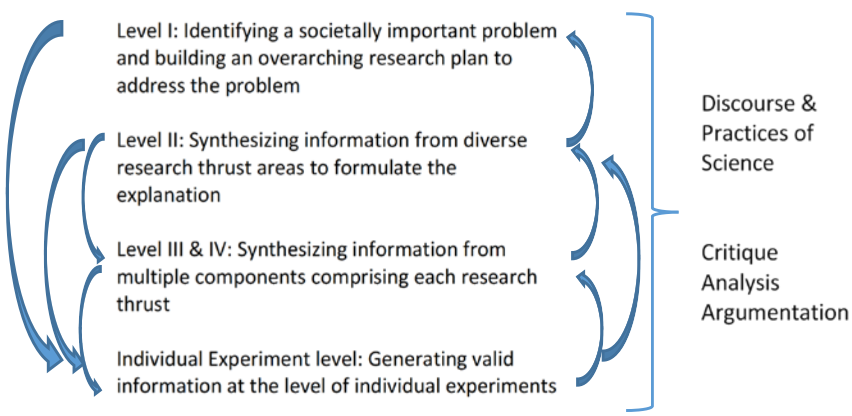
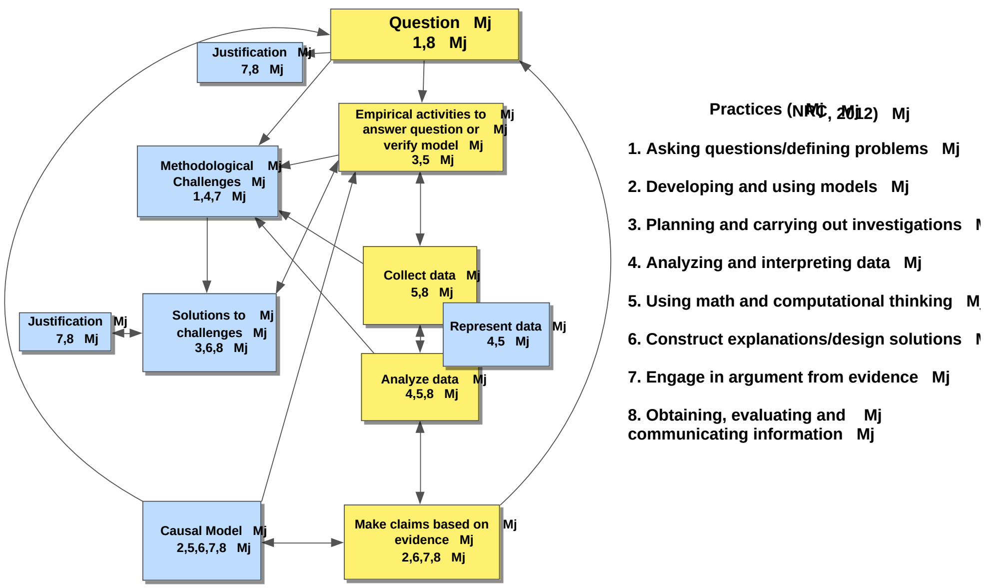


Figure 3. Summary of flow of activity and information building over the course of the research

Another important feature of the M-model Framework for teacher PD is the detailed depiction of activities within an individual experiment. For experienced researchers, much of what actually happens here becomes routine such that the intricacies of the processes are internalized. Unless the routines are explicitly discussed with teachers, they remain hidden. Figure 4 summarizes the kind of hidden thinking inherent when experimenting, and provides links to the science and engineering practices outlined in the NGSS *Framework* (NRC, 2012).



<u>Using the Master Model with Teachers and Graduate Students</u>

Although we have been using the M-model in a variety of PD contexts, each PD utilizes a similar process for introducing the M-model. As a first step, we present and discuss the definition of systems thinking and examples of systems diagrams representing complex natural phenomena such as the water cycle, or food web, or energy cycles, and man-made systems, such as engineered systems, business organizational systems and governmental systems. We discuss how these diagrams provide mental models of the system, showing interconnections and interdependencies across the system, and enabling (make apparent) predictions of how changes in some component of the system might impact other components and the system as a whole. We then introduce the idea of applying systems thinking to the design and implementation of a research project. At this point we present the M-model Framework Level I diagram of an active research project showing the recursive pattern of levels and interconnections. If the PD is related to a specific research project, we have one of the research faculty describe the project, referring to the Framework diagram. However, if the PD has no relationship to any particular research project, we use an example from a previous project whose components are now public knowledge. The description of the research project includes discussion of the process of refining the guiding question or overarching goal, as well as how findings from various individual tasks combine with others to contribute to answering the overarching question. We also discuss how such new information informs decisions at the subcomponent and component level, such as whether to change or eliminate a particular approach or experiment. We then present and discuss the template for the M-model, as depicted in Figure 2.

At this point our use of the M-model diverges depending on the audience's prior knowledge and experience with research. With teachers we begin by using the M-model Framework as a guide for situating the discussion. We involve them in discussions and activities related to various components and subcomponents of the featured authentic research system. Activities include learning about procedures and techniques used in the actual research process, working with actual data from the research project, and developing classroom investigations that parallel aspects of the authentic research project and incorporate the M-model. Discussions include some of the challenges researchers encountered in areas such as data collection and analysis, as well as how findings from the experiments impact other parts of the research system or draw into question underlying assumptions. These activities and discussions are intended to familiarize teachers with an authentic research project and reinforce the system dynamics of the research process. We then have them use the MASTER Model to design and carry out a classroom research project. In some cases, teachers engage their students in classroom projects that parallel the ongoing authentic research project, using the M-model for planning and anticipating interrelationships, and techniques and procedures learned from the PD activities. In the case of the PD program where we work with local school districts, this process is extended into the academic year.

Our use of the M-model with graduate students participating in the PD takes on a different form. The graduate students are all working on a research project intended to be the source of their dissertation work. These projects focus on particular components of a larger research system comprising the advisor's overall research agenda. In order to ground the M-model in their own experience, we ask each graduate student to use the M-model to diagram his or her own research project, indicating how various components of their project interrelate and are interdependent. After they share their diagrams, we ask them to expand the boundaries of their project's research system to incorporate other projects in the research lab, and/or in other labs linked via a common research grant. Once again, using the M-model Framework students include areas of interconnections and interdependencies across projects. Finally, we have them expand the boundaries further to consider the broader research spaces to which their research pertains, based on readings of literature and discussions at conferences. We then have them consider how to apply the M-model to the teacher PD activities, such as making presentations about their research and how it relates to the overarching research project, engaging teachers in inquiry-based activities associated with ongoing research of the project, and helping teachers plan classroom research projects.

Teacher, Graduate Student and Faculty Interactions with the MASTER Model

We are still in the early stages of applying the M-model in our teacher PD programs and have been incorporating different aspects of the M-model with various elements of different programs, so the patterns here represent work-in-progress. Our observations so far are based on informal focus group discussions and interviews with teachers and graduate students who participated in the various programs, as well as anecdotal comments and questions arising during the PD and classroom activities.

Graduate Students/Faculty

- Although their research plans had already been designed, graduate students found that the M-model provides greater clarity of understanding about their projects, and helps them form concrete connections between ideas and topics.
- Use of the M-model helps graduate students organize findings from large amounts of data, enabling them to see outcomes, connections, and holes in the study.
- Graduate students find that the M-model is very useful for conveying ideas to others. Several used it in meetings with their research advisors (who liked it very much), and found that it led to more focused and efficient dialog. Several plan to incorporate the framework into their dissertations to better communicate how they see their projects, connect components, and see what is missing.

Teachers

- Using the M-model in connection with an authentic research project impacts how teachers think about research. It helps them see how experiments they have their students perform are associated with larger, broader topics.
- Exposure to discussions and activities associated with an authentic research project coupled with the M-model Framework's depiction of the systems nature of the research emphasizes the messy, non-linear nature of research and helps teachers move beyond the traditional Scientific Method and recognize the teamwork associated with research, in which many people work toward a common goal.
- The systems thinking aspect of the M-model is helpful in lesson plan development as a framework to guide the design process of the lesson such as what variables should be investigated.

Graduate Student, Teacher, Student Interactions

- When referring to the authentic research project, having a model to represent the overarching research plan and its various components and subcomponents helps teachers, students, and graduate students (1) understand the systems-based organization and complexity of research projects, and (2) situate discussions about the role of the various components and subcomponents, and activities and discussions focusing on individual experiments or tasks.
- The M-model is a helpful tool for graduate students to use when communicating their own research to teachers, and how it fits with the overarching research plan.
- Using the M-model Framework and applying a systems thinking perspective for developing classroom research projects helps teachers and graduate students co-design classroom research and engineering design projects and plan logistics for their implementation.
- The M-model is also helpful while working with students to plan and implement research projects. In the planning stages, information from reading about particular components or subcomponents can be added directly to the framework. During implementation, findings can be added and plans altered depending on those findings.

Implications and Next Steps

The M-model applies the cross-cutting concepts of systems thinking and model-based reasoning within the context of an authentic research project to enhance teachers' and students' understanding of the nature of research. It is designed to capture the complexities of authentic research in both the planning and implementation phases, in ways that emphasize the systems nature of research and promote development of methodological and intellectual proficiencies associated with research. It provides a representation of the research process that allows various aspects of research to be examined in detail, and combined to represent the whole. There are numerous functions associated with the model, including: (1) a scaffold for applying a systems thinking approach to planning and describing a research project; (2) once completed, a framework or roadmap for situating the various component systems and subsystems comprising the research and their interconnections; (3) a reminder of points of discourse, thinking processes and interactions among researchers that occur at all levels of the research process and which need to be made explicit; and (4) a representation of research as a dynamic, evolving process with internal feedback loops through which findings from individual investigations within components yield new information that builds understanding within and across systems levels.

Duschl et al. (this volume) describe in detail the value of the NGSS approach for providing learning that integrates cross-cutting concepts, the discourse and practices of science with content learning, in a way that mimics the work of science and engineering. They also present evidence for the capability of K-12 students to successfully engage in this type of learning when elements are appropriately sequenced and adequate ongoing support is provided. However, preparing teachers to provide that ongoing support remains a key issue associated with implementation of NGSS. Borko (this volume) stresses the need for teacher PD to help teachers understand the elements associated with the NGSS approach, and be able to use them in their teaching. Borko also provides a plan reflecting best practices for teacher PD that will help teachers understand and implement aspects of model-based reasoning. Such a plan could be applied to a number of individual cross-cutting concepts and practices for teachers. However, attention to individual elements in the absence of understanding the big picture of how they fit together may serve to isolate these elements rather than promote their synthesis. The M-model can provide a big picture perspective of how these elements work together in authentic STEM research, and how to translate that perspective into classroom science teaching. Part of its use can include explicit reference and discussion of the individual NGSS elements and how they occur at all levels of the research process. This strategy could be used in combination with more specific attention to individual cross-cutting concepts and practices, enabling teachers to understand how the parts fit into the whole.

All of our programs involve connections to authentic research projects and researchers, however our use of the M-model in PD has varied, depending on the context of the program, types of opportunities for graduate student involvement, and the extent of involvement by graduate students and faculty. Our preliminary observations suggest that the M-model is working to enhance teachers' understandings of the systems nature of authentic research and is helping them see how the M-model can be used for designing and implementing classroom research projects. There are a number of research directions we would like to take using more systematic approaches in order to enhance PD in this area. We would like to explore in what ways and to what extent the M-model process influences teachers' understanding of the nature of research and their ability to translate that understanding to the classroom in the form of classroom research projects and model-based inquiry lessons.

A related area of interest is to examine how the M-model can be used most effectively across PD types that vary in how closely associated teacher involvement is with the authentic research project and the degree of graduate student or faculty interaction. Our programs range from six-week summer immersion TREs mentored by STEM faculty and graduate students to one-day episodic workshops led by STEM faculty or graduate students. We would like to understand how teacher understanding from these various PD opportunities differ, and how we can maximize learning from each type of experience. For example, a review of the literature on impacts of immersion research experiences, Sadler, Burgin, McKinney and Ponjuan (2010) found mixed results on the value of such experiences to effect change in classroom teaching. Teachers often return to the classroom excited about the experience but unprepared to incorporate what they have learned into the classroom. We hope to investigate in what ways and to what extent incorporation of PD based on the M-model helps teachers translate learning from an authentic TRE into their teaching.

We are also interested in exploring use of the M-model as a mechanism for teacher learning about the Nature of Science (NOS). An important goal of the NGSS is for students to develop basic understandings about (NOS). These understandings are evidenced by the work that scientists and engineers do, and relate to the methodological and intellectual proficiencies that are acquired over the course of their professional continuum as researchers. Because teachers have only limited exposure to authentic research and apprenticeship with researchers, they have limited opportunities to experience these themes and understandings in action. The M-model, used in conjunction with teacher PD associated with an authentic research project, provides opportunities to explicitly address many of the NOS elements. Having learned how these understandings apply to authentic research via PD that explicitly addresses them, teachers will be better equipped to use them within the context of classroom research or model-based inquiry lessons.

The most surprising outcome from our initial observations has been the impact of the M-model process on graduate students. Our initial purpose for engaging graduate students with M-model was to familiarize them with the strategy we planned to use for the teacher PD, so they could use it with teachers to help to convey the nature of research. However, we are finding that the M-model is helping the graduate students on a personal level to conceptualize their own research projects in ways that are different than they were doing previously. Some of these changes seem to be related to advanced methodological as well as intellectual proficiencies described by Feldman et al. (2009), such as situating their research within a greater whole, organizing large data sets for analysis, and communicating their research findings in a more organized and efficient way. We are in the process of developing investigations into these and other potential impacts, and how the M-model can be used with faculty/graduate student pairs to enhance graduate students' understanding of the research enterprise. We expect that its value for helping students better understand the nature of research will also apply to undergraduate students as well.

Connecting all of these applications to learning about the nature of research are the basic cross-cutting concepts of systems thinking and model-based reasoning that underlie the M-model approach. The model depicts research as a complex system of interrelated and interdependent parts whose boundaries can be expanded or retracted depending on the purpose in which it is being used. Model-based reasoning applied to the complex system allows investigation into the workings of authentic research projects at numerous levels of detail, as well as predictions and implications of changes across the system, causing it to evolve. These are characteristics of systems thinking and model-based reasoning employed in the study of natural phenomena (e.g., Assaraf & Orion, 2005). Based on our preliminary findings, we believe that these cross-cutting concepts, when applied to authentic research projects, will lead to deeper understanding of the research enterprise to the benefit of students at all levels.

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