Mathematics and Science Teacher Preparation:

A Primer

A Synthesis of Research
Reviewed by the Ohio Board of Regents
Teaching Fellows in Mathematics and Science

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OHIO BOARD OF REGENTS TEACHING FELLOWS

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RATIONALE

"We are the pioneers of Ohio's third frontier – a frontier of exploration and discovery where knowledge is king."

– Governor Bob Taft
State of the State Address,
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If Ohio is to successfully compete in today's knowledge economy, our high school graduates most be more scientifically and mathematically literate. We need to equip students with these capabilities in order to pursue higher education and high-technology careers that can sustain and grow Ohio's economy. Ohio's ability to develop, attract, and support high-tech business and industry with a technically competent work force will be one of the keys to the state's future prosperity.

The Ohio Board of Regents initiated the Teaching Fellows program to enhance quality in the preparation of mathematics and science teachers. The program represents an opportunity for all colleges and universities in Ohio to engage in inter-institutional dialogue about practices that can enhance educational professional development with a particular emphasis on preservice teachers.

As the "Glenn Report" (U.S. Department of Education, 2000) and others indicate, the most direct way to improve education is to have high-quality teaching in those disciplines. Higher education faculties must assume a substantial responsibility to promote high-quality teaching. Teachers must be well-grounded in content knowledge, fully licensed, and capable of raising the achievement levels of their students. Thus, science and mathematics faculty must teach not only with an eye toward preparing students for professional and graduate programs, but also with the realization that they are preparing teachers who will educate the next generation of scientists and mathematicians. When students enter college science and mathematics programs poorly prepared, the quality of K-12 teaching is often suspect. The question needs to be asked, "Who educated those teachers?"

Higher education faculty also must reflect upon how and what they teach. College-level content courses should model innovative and effective instruction, focusing on the depth of content understanding and providing opportunities for future teachers to "do science" in realistic settings. Higher-quality teaching in the college classroom can bring about higher-quality teaching in the K-12 classroom.

PROGRAM GOALS

The Ohio Board of Regents Teaching Fellows program was created to enhance the quality of teacher education practices in mathematics and science education. Working on two basic assumptions, the fellows program has established the goals and initiatives that follow.

Program Assumptions

- The foundation of knowledge rests with each disciplinary area. Educators from **education and arts and sciences must come together** to decide what content should be emphasized.
- The effective delivery of teacher education programming is influenced by **meaningful collaboration with partner sites in P-12 schools.**

Program Goals

- To assist Ohio institutions in designing programs that align with emerging P-12 standards; better prepare teachers for success on the PRAXIS exams; and ensure that prospective teachers possess the academic content necessary for teaching in their assigned licensure areas.
- To identify institutions whose graduates are having difficulty passing the PRAXIS exams in mathematics and science-related areas and to assist them in creating strategies that strengthen programs and foster student success on required examinations.
- To identify program characteristics common to effective programs and to foster dialogue among all 50 colleges and universities regarding the transportability of these characteristics.
- To identify programs and educational practices that enhance the national visibility of Ohio's high-quality teacher education programs.
- To identify ways of strengthening the capacity of institutions that prepare mathematics and science teachers through enhanced dialogue and communication among all teacher-interest groups.

Program Initiatives

- Statewide conferences for mathematics, science, and education faculty in 2003-2005.
- Higher education institutional visits throughout Ohio to selected teacher education institutions with preparation programs in mathematics and science.

- Development of a research primer and a case-study portfolio related to current issues and practices in mathematics and science education.
- Development of a higher education survey instrument focused on institutional variables affecting motivation and capacity to change.
- Formation of an advisory committee to the Ohio Board of Regents on issues of mathematics and science education.

CURRENT RESEARCH ISSUES

One of the directives of the Teaching Fellows program is to review current educational research in an effort to link research to relevant application in the preparation of mathematics and science teachers. The ultimate goal is to improve the quality of science and mathematics education in Ohio. The 2002 National Research Council's "Principles of Scientific Research" guided the selection of studies reviewed. Basic guiding criteria included:

- Empirically based research
- Peer-reviewed, published research within the past 20 years
- Rigorous research as defined by the NRC and meeting generally accepted standards in relevant research traditions

Examples of reviewed research included: longitudinal change; experimental and quasi-experimental; survey; correlational; and comparative descriptive research. As resources, the fellows relied heavily upon "Teacher Preparation Research: Current Knowledge, Gaps, and Recommendations" (Wilson, Floden, & Ferrini-Mundy, 2001) and "Eight Questions on Teacher Preparation: What Does the Research Say?" (ECS, 2003).

To meet the "Well-Supported Research" designation listed below, the research was required to meet one of the following standards of rigor:

a. Random assignment to group or some form of matching characteristics for experimental and quasi-experimental studies.
b. Multiple regression and comparative studies "controlled" for relevant differences among subjects other than teacher education or certification received.
c. Longitudinal studies of change checked for effects of attrition with evidence that changes were not simply due to maturation and teaching experience.
d. Interpretive studies including a description of their processes for data collection and analysis as well as evidence (e.g., samples of interviews).
e. Surveys wherein questionnaires were sent to representative samples with return rates of 60 percent. Inferences made in the reports were restricted to perceptions of the respondents (Wilson et al., 2001).

Moreover, research was considered "well-supported" if multiple studies had been completed and reached similar conclusions.

Because of the significant challenges faced in performing educational research by the standards above, the existing "well supported" research provides a general base to guide teacher preparation, but specific information for improvement of programs is limited.

Well-Supported Research

1. **Teachers' subject matter preparation is correlated with higher student achievement in mathematics and science and with higher teacher performance (Darling-Hammond, 2000; Goldhaber & Brewer, 2000; Guyton & Farokhi, 1987; Monk, 1994).**

Research has demonstrated a positive correlation between teachers' subject matter preparation in mathematics and science and higher student achievement in those areas. A strong content knowledge background is linked to increased teacher effectiveness in the classroom. Some researchers have found that variations in content knowledge among preservice teachers are problematic. While their factual and procedural subject area knowledge may be strong, their conceptual and organizational knowledge of the subject may be weak. Comprehensive content knowledge is necessary to help them teach subject content to their students in meaningful, effective ways. In other words, prospective teachers may need to gain a better understanding of the subject matter within the constructs of pedagogical knowledge. Therefore, additional research is needed on the nature of subject-specific methods courses, especially as the clinical nature of such courses is explored. While research has indicated that changes in teacher preparation programs are necessary to increase teacher effectiveness, the resolution most likely will be more complex than the mere requirement of additional content courses. For example, subject-specific methods courses may be as important to improving teaching effectiveness as subject-specific content courses. Though many complicated variables such as these must be considered in the development of a solution, educators cannot ignore research findings that indicate a significant relationship between teachers' content knowledge and student achievement.

2. **Traditionally styled mathematics and science instruction does not produce depth of content understanding or promote skills of inquiry (Adams, 1998; Ball, 1990; Borko, Eisenhart, Brown, Underhill, Jones, & Agard, 1992; Stoddart, Connell, Stofflett, & Peck, 1993; Gess-Newsome & Lederman, 1993; Graeber, Tirosh, & Glover, 1989; McDiarmid & Wilson, 1991).**

Substantial debate has occurred since the early 1900s about the relative merits of traditional, teacher-centered education (e.g., lecture-oriented) as opposed to progressive, student-centered education (e.g., inquiry-oriented). Clear research justifying one approach over the other for all P-16 (preschool through undergraduate) students simply does not exist. Prevailing literature provides evidence of the relative merits – as well as the limitations – of each. Indeed, the famous Eight-Year Study conducted in the 1930s of high school students (Cremin, 1961) found no significant differences between students taught in experimental student-centered educational environments (where more open-ended inquiry was emphasized) and those educated in more traditional, teacher-centered environments (where more structure was evidenced). The minor differences that did exist between the groups favored student-centered approaches. Traditional approaches may be most appropriate for beginning learners who are trying to acquire essential knowledge and skills. More progressive, student-centered approaches may be more appropriate for students who already possess certain requisite understandings and can use that knowledge to explore content in greater depth, especially when in the classroom of a teacher or professor who is capable of guiding the learning process and who understands how context may influence the guidance of learning.

3. **The knowledge of how to teach mathematics and science (e.g., specific teaching strategies) is important in addition to the comprehension of the subject itself. Subject-specific pedagogical preparation impacts teacher effectiveness (Monk, 1994; Gess-Newsome & Lederman, 1993; Adams & Krockover, 1997; Grossman & Richert, 1988; Guyton & Farokhi, 1987; Ferguson & Womack, 1993).**

   Substantial evidence supports the contention that subject-specific teaching-methods courses (pedagogical preparation) for preservice teachers has a positive effect on student achievement. Within teaching-methods courses, preservice teachers specifically need to learn how to select and organize content for optimal student learning. Student achievement also correlates with levels of teacher certification. Fully certified (and experienced) teachers appear more capable of successfully engaging students with subject matter. Often, secondary teachers with high content mastery and no pedagogical preparation are limited in their ability to meaningfully engage high school students and foster learning in the subject matter.

4. **Teacher preparation programs that include content on classroom management, learning theories, and curriculum development are correlated with higher student achievement (Felter, 1999; Schelske & Deno, 1994; Darling-Hammond, 2000; Goldhaber & Brewer, 2000; Hawk, Coble, & Swanson, 1985; Ferguson & Womack, 1993).**

   Preparing preservice teachers to manage classrooms, select and organize content for classroom delivery, and understand and apply theories of how students learn is correlated positively with their subsequent effectiveness as teachers. Higher student achievement is attributed both to increased time for student learning in better-managed classrooms and to teaching activities and strategies that encourage and permit student connection with subject matter.

Emerging Research

The **"Emerging Research"** category includes conclusions from studies that **may or may not** have met the "well-supported" standards of rigor. In addition, fewer studies may support the findings, indicating that future research would be needed to corroborate the conclusions. However, the research was judged by the Teaching Fellows as likely to have significant impact in preservice mathematics and science teacher education.

1. **Interactive teaching methods, such as inquiry and problem-based learning, enhance student comprehension of subject matter (Driver, Asoko, Leach, Mortimer, & Scott, 1994; Tobin, McRobbie, & Anderson, 1997; Cohen, 1994; Brophy & Good, 1986; Resnick, 1987; Trowbrige & Bybee, 1990).**

   Research has led to the development of mediated forms of inquiry, in which the role of the teacher is to elicit students' existing mathematics and science knowledge, introduce new ideas in the context of hands-on/minds-on activities, and direct learners' ideas toward accepted scientific concepts. Inquiry has been viewed as having a discursive dimension that complements the dimensions of critical thinking and individual skill with mathematics and science processes. Inquiry may take a number of forms: discovery learning, in which the teacher sets up the problem and processes but allows the students to make sense of the outcomes on their own, perhaps with assistance in the form of leading questions; guided inquiry, in which the teacher poses the problem and may assist the students in designing the inquiry and making sense of the outcome; and unguided inquiry, in which the teacher merely provides the context for solving problems that students then identify and solve.

2. **Pre-existing knowledge influences the way new knowledge is added to each student's conceptual model, modifying its subsequent meaning (Stahl, 1991; Marion, Hewson, Tabachnick, & Blomker, 1999).**

   To be effective, teachers must learn how to listen to students and probe various conceptualizations, then use this knowledge to frame the way the concepts should be taught. Pre-existing knowledge influences the way new knowledge is added to an individual's conceptual model, modifying its subsequent meaning. Knowing the prior cognitive states of the learner, including specific preconceptions about the natural world, leads to a reconsideration of the context and purposes of inquiry.

3. **The science-technology-society (STS) "connecting movement" is an emerging paradigm for enhancing teaching and learning in science and/or mathematics in context (Harms & Yager, 1981; Lewenstein, 1992; Bybee, 1993; Bybee & McInerney, 1995).**

True learning is a process of making sense of experiences rather than just memorizing information. It requires the integration of thoughts, feelings, and actions. Meaning is constructed by adding, deleting, and modifying information into an existing conceptual framework. A goal of contemporary education is to develop "literate" individuals who are aware of the mutual dependency of science, mathematics, technology, and society and are able to use their acquired knowledge in everyday decision-making. The scientifically and/or mathematically literate person has a substantial knowledge base of facts, concepts, and conceptual networks, as well as skills that enable the individual to learn logically and independently. Such individuals see the value as well as the limitations of science, mathematics, and technology in society. Evidence suggests that students who acquire understanding in experiential formats (through inquiry approaches) are better able to study and learn on their own, be that in academic, personal, or professional contexts.

4. **Sequencing of content activities has been shown to be a factor in teacher effectiveness. Therefore, teachers should be proficient in using a variety of available instructional models to increase student comprehension and achievement (Karplus, Lawson, Wollman, Appel, Bernoff, Howe, Rusch, & Sullivan, 1977; Bybee, Buchwald, Crissman, Heil, Kuerbis, Matsumoto, & McInerney, 1989; Biological Sciences Curriculum Study, 1993).**

Since sequencing of activities has been shown to be a factor in their effectiveness in terms of student learning, teachers should be proficient in using available instructional models such as the learning cycle or other demonstrably effective constructivist models. Well-prepared science teachers can plan, implement, and evaluate a high-quality, standards-based science curriculum that includes long-term expectations, learning goals and objectives, plans, activities, materials, and assessments, all anchored to established academic content standards.

5. **Culturally relevant teaching helps science and mathematics come alive for many students, especially those who have been traditionally uninvolved in science or mathematics (Atwater, Crockett, & Kilpatrick, 1996; Ladson-Billings, 1995; Atwater, 1994; Weld, 1990; Ford, 1993; Nieto, 1992; Patthey-Chavez, 1993; Rivera & Poplin, 1995; Greenberg, Rhoades, Ye, & Stancavage, 2004; American Psychological Association, 1992; Kahle, 1983; Banks, 1993; Orlich, Harder, Callahan, & Gibson, 1998).**

Many factors shape a student's conceptual framework, including: life experiences; social, emotional, and cognitive developmental stages; inherent intelligences; learning styles; race and gender; ethnicity and culture; and demographic setting. Teachers must be aware of the influences of these factors – real or potential – on student behaviors and abilities if they are to design effective learning opportunities. Though teachers may not know a large amount about the families and communities of some of their students, they should, with the information they do have, be able to provide examples, analogies, and investigations based upon students' personal experiences and on cultural contexts. This promotes curiosity and helps students build a personally meaningful framework for their educational growth. Teachers also should be aware of additional steps they can take to meet the needs of all learners, from customizing equipment and adapting lessons to using cooperative learning approaches.

Pedagogical Content Knowledge

The Teaching Fellows believe the concept of pedagogical content knowledge offers significant potential for linking arts and sciences with colleges or departments of education and, more often then not, the traditionally separated knowledge bases of content and pedagogy. Pedagogical content knowledge was first proposed by Shulman (1986) and developed with colleagues in the *Knowledge Growth in Teaching* project as a model for understanding teaching and learning (e.g., Shulman & Grossman, 1988). As such, pedagogical content knowledge has been described as the knowledge formed by the synthesis and integration of four knowledge bases: subject matter knowledge, pedagogical knowledge, knowledge of environmental context, and knowledge of students. Pedagogical content knowledge can be viewed as a transformative knowledge base that is unique to highly effective teachers and separates a teacher who is prepared professionally from an individual with only content preparation. In other words, the science or mathematics teacher's knowledge base must include not only a scientist's or mathematician's comprehension of the content, but also an educator's understanding of how to foster that knowledge within students. Similarly, in mathematics education, "it is widely accepted that knowledge and understanding of students' mathematical learning is important for teaching" (Even & Tirosh, 2002). Magnusson, Krajcik, and Borko (1999) conceptualized, for example, pedagogical content knowledge for science teaching as consisting of five components:

1. "Orientations toward science teaching," consisting of the beliefs about the purposes and goals of teaching science at different grade levels.
2. "Science curriculum knowledge," consisting of knowing about the goals and objectives of curricula (state, national, and vertical) and knowing about specific curricular programs.

3. "Knowledge of the students' understanding of specific science topics," involving knowing the requirements of learning and the areas of student difficulty.
4. "Assessment," involving the knowledge of specific instruments, procedures, approaches, and activities for assessing specific student content understandings.
5. "Instructional strategies," including knowing subject-specific strategies, topic-specific strategies, and situation-specific pedagogical content knowledge (Veal & MaKinster, 1999).

TEACHING FELLOWS' RECOMMENDATIONS FOR THE FUTURE

- Education students need to experience active learning within their mathematics and science content courses.
- Education students need to see pedagogical content knowledge modeled in their mathematics and science content courses. Pedagogical content knowledge refers to the way in which teachers bring together the content with knowledge about how best to teach that content. Pedagogical content knowledge issues need to be addressed in more education and content courses than "subject methods" courses.
- Given the transformative nature of pedagogical content knowledge, seminars in methods and pedagogical content knowledge should be taught in coordination with mathematics and science content courses. This would facilitate the integration of the knowledge bases (subject matter knowledge, pedagogical knowledge, knowledge of environmental context, and knowledge of students). The importance of pedagogical content knowledge lies in teachers' abilities to build a bridge between the previous knowledge and experiences of their students and new content knowledge, thereby making the new knowledge relevant and personally meaningful.
- A clearinghouse should be created for the collection, categorization, and dissemination of information about pedagogical content knowledge, which would then be made available to all the stakeholders such as mathematics, science, and education faculty. Efforts should be made to consolidate existing information as well as establish, identify, and classify new information.
- The efficacy of pedagogical content knowledge should be empirically verified through peer-reviewed research, including doctoral dissertations, in order to learn what distinguishes high-impact pedagogical content knowledge from less effective pedagogical content knowledge.
- Proactive pedagogical content knowledge development projects should be defined and proposed for funding as a way to start an organized, more systematic investigation of pedagogical content knowledge, particularly in subjects where limited understandings of it exist.

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OHIO BOARD OF REGENTS

Goals

Three themes guide the work of the Ohio Board of Regents:

- Ohio must close its higher education deficit by better educating more of its citizens.
- Ohio must ensure that its workers can compete in the "knowledge economy" of the 21st century by continuously training and retraining its work force.
- Ohio must advance the success of its businesses and create new economic opportunities for all Ohioans by increasing the state's investments in commercially focused university research.

Central to the accomplishment of these goals are efforts to improve education from the time the student enters the preschool setting up to and including success in higher education. Ohio's PK-16 agenda provides guidance for efforts to improve student achievement and enhance teacher effectiveness, particularly in mathematics and sciences.

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