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A Contract for Excellence in Scientific Education: May I Have Your Signature Please?

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A CONTRACT FOR EXCELLENCE IN SCIENTIFIC EDUCATION

MAY I HAVE YOUR SIGNATURE PLEASE?

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Recent advances in biology and digital technology represent unique opportunities for teacher educators to rethink the programmatic experiences of prospective secondary science and mathematics teachers. This article discusses the importance of teacher education programs that connect mathematics and science where appropriate, recognize the hybridization of science, and integrate biological and digital features into program learning experiences. In addition, recommendations for incorporating these design features into teacher education are offered.

Keywords: *collaboration; educational reform; foundations of education; mathematics education; program standards/evaluation; science education*

> We have entered into a . . . Jeffersonian compact to enlighten our children and the children of generations to come.
>
> —U.S. Department of Education (1991, p. 80)

> It is imperative that we encourage students to master the critical fields of math and science. At the dawn of the 21st century, they've never been more important.
>
> —Secretary of Education Spellings (2005)

Why are math and science critical? This pressing policy concern will guide our discussion on the education of secondary teachers of mathematics and science. Science and mathematics attainment have been linked to modern political thought since the inception of the nation (Kamens & Benavot, 1991). Calls for quality scientific education in the United States are quite common in policy circles and by leading officials in this country. Thomas Jefferson articulated a human resource scheme to advance the mathematical and scientific progress of an early America. Two centuries later, the presidential administration of George H. W. Bush signaled the country that a significant investment in human development broadly defined to include scientific education was required (U.S. Department of Education, 1991). Moreover, the language of this particular call—

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a compact—suggests there was a need for a signatory. Who will provide the signature? We argue that teacher educators should consider developing signature programs of study in the sciences broadly defined to include mathematics. The term *signature* has at least one definition relevant to this discussion of preparing scientifically competent teachers.

Signature, in this article, is used to describe programmatic distinctiveness. It is very common in today's marketing-savvy world to have corporations discuss their signature products. In theory, a signature product is an item or service that represents the very best qualities of a commodity being sold. The signature product has transparent features that distinguish it from other brands. To this end, the biological and digital worlds represent important opportunities for teacher educators. Each represents a potential signature moment for producing distinct teacher education programs.

A MARK OF DISTINCTION: CONNECTING MATHEMATICS AND SCIENCE

Distinction in the preparation of science and mathematics teachers is feasible as teacher education programmatic goals and experiences, where appropriate, more closely align with the experiences in the scientific domain. Most of what takes place in mathematics and science education is simulated curriculum. Specifically, the student learning experience is largely devoid of many of the characteristics associated with authentic action in the domain. Newmann, Secada, and Wehlage (1995) argued that opportunities to learn school subjects, including mathematics and science, should be aligned with the practices of the discipline. In the case of mathematics and science, the learning experience should require the students to organize, synthesize, interpret, evaluate, and/or explore alternative solutions (where appropriate) and methods in addressing a concept or problem. In addition, opportunity to learn mathematics and science should require students to demonstrate understanding of big ideas and theories, methods of analysis, and discipline-specific communication. Finally, Newmann et al. argued that appropriate student learning opportunities should include working on problem situations they are likely to experience in life outside the classroom while providing opportunities to communicate their findings to an audience beyond the school setting.

The discussion of distinctiveness thus far focuses on student learning of mathematics and science. However, it is logical to assert that if students are to experience an authentic mathematics and science education, then prospective teachers must be able to implement it. In both fields of teacher education, there is a tendency to reduce the relationship between mathematics and science to very artificial relationships that minimize the coactions of mathematics and science in the advancement of ideas and innovation (American Mathematical Society, 2001; Anderson & Mitchener, 1994).

In many problem settings, mathematics and science coact in powerful ways to produce new knowledge. It should be obvious to all who teach science that an important part of the scientific method includes recording and interpreting data. Yet the role of mathematics is more expansive than this integral component of scientific practice. Scientists use three approaches in their research—observation and experiment, theory, and modeling. Each approach is required to understand the multifaceted phenomena studied today by scientists and engineers, and each approach incorporates the mathematical sciences (Wright & Chorin, 1999).

The problems faced by scientists and engineers are so difficult that many of the challenges can be solved only through the assistance and participation of mathematicians. The ability to follow scientific arguments as citizens or to engage in science as a participant in a discipline is enhanced with more advanced mathematical skills and conceptual understanding. It is a great advantage for students in secondary and middle schools to see mathematics as integral to science (National Council of Teachers of Mathematics, 2000). Students with significant mathematical preparation in their school science programs have more opportunities to learn mathematics and to advance to the academic level required to understand the complexity of today's scientific enterprise (Kaput, Noss, & Hoyles, 2002; Tate & Johnson, 1999). Additional opportunities to learn mathematics are critical as disciplines such as chemistry and physics that have always been mathematical are becoming even more so. Sciences that have not had a strong mathematical focus in the past (e.g., biology, physiology, and medical research) are shifting from descriptive explanation and taxonomy to more sophisticated analysis and explanation; many research problems involve systems that are not transparent and, thus, this uncertainty demands exploration with new mathematical tools (Wright & Chorin, 1999). Ignoring some level of uncertainty can be justified when a scientist is studying an isolated, small-scale, well-documented physical process. This is not the case when a study involves large-scale systems such as black holes or the oceans, chemical processes where describing reaction paths is challenging, and, of course, in biomedical applications or in systems that depend on human participation. Uncertainty cannot be addressed appropriately using loosely defined strategies but requires intense mathematical study and the use of complex models.

The Role of Models in Science

The use of models and the process of creating mathematical models are vital to both scientific education and the practice of science. Model building can begin in kindergarten and should extend through high school (National Research Council, 1999). Numerous opportunities should exist for students to engage in the model development cycle—model construction, model evaluation, and model revision. This cycle mirrors the process many in the scientific community use. Wright and Chorin (1999) argued that mathematical modeling, a strategy for describing relationships and actions in a mathematical framework, brings the powerful machinery of mathematics and its ability to generalize to draw on what is common in a variety of problems and to build effective algorithms to bear on characterization, analysis, and prediction in scientific problems. Mathematical models serve as virtual experiments whose real-world analogues would be cost prohibitive, life threatening, or outside the bounds of human construction; they obviate the need to actually crash an oil tanker, spread a deadly bacteria, or witness a geologic occurrence. Mathematical models inform our understanding of relationships within a system, as well as the relative significance of components within the system. Through modeling, estimates about a system are given a structure that provides a format to examine them qualitatively and quantitatively from numerous perspectives and conditions; in particular, modeling provides insights into potential discrepancies between theory and reality.

Consider the case of meteorology. This field of science was largely descriptive in nature, not scientific, and underdeveloped mathematically until it was feasible to link quantitative measurements of atmospheric pressure. Imagine today if your weather forecasting was limited—with restricted predictive power as well—to "dark sky at 11:00 a.m., storms possible" and other descriptive language. Instead, a technical advancement in the form of the barometer and the associated mathematical framework greatly informed the science of meteorology. Our improved understanding of upper-air jet streams and advanced photography produced by satellites in conjunction with quantitative models from mathematical physics to inform the data analysis have resulted in better weather prediction (Wright & Chorin, 1999).

Modeling as a process is particularly relevant for prospective science and mathematics teachers because the knowledge base in mathematics, engineering, and science is growing and changing rapidly, yet the time and opportunity to cover every big idea in these fields is relatively constant. Consequently, providing prospective teachers with example problems that foster their understanding of the modeling process is one way to develop their skill sets in a fashion that is applicable across the expanding scientific knowledge base. Model-based approaches to teacher learning advance an important type of scientific literacy.

Language and Hybridization

The role of mathematics in science is multifaceted. Another important role that mathematics plays in science is as a common language to communicate across the sciences. During the past 30 years, there has been a trend toward integrating fields of scientific research that originated in separate disciplines. Cutting edge science in the 21st century is likely to unfold among, not within, fields of scientific study. Physicists, mathematicians, and engineers, concerned with producing mathematical models of complex systems, are and will continue to provide powerful insights and methods to biologists and neuroscientists. Conversely, biological systems represent a different and challenging site of study for mathematics and physics, and further interdisciplinary research in biology, mathematics, and physics stimulates technological advances in engineering and computer science.

Examples of these hybridizations are biophysics, bioinformatics, geophysics, molecular biology, genetic engineering, neuroscience, and hundreds more. What do they have in common? Each uses the language of mathematics to describe data, trends, and the process of data analysis. At one level the term *data* refers to presentational aspects of the phenomenon under study. The data of phenomena are mapped onto words or numbers. This mapping is called measurement. The quality of all data analysis depends on the quality of the measurements. Good science requires the ability to measure in a variety of ways. Technology helps the scientist to measure. Often the scientist must measure large amounts of data and, thus, an aim of analysis is to reduce the data to a summary that makes sense and is consistent with established norms of communication (i.e., mathematics). Calculating measures of central tendency (e.g., mean, median, or mode), variability (e.g., range), and shape (graphic representation) can effectively reduce 700 data points to 3 and at times, the essential characteristics of data are not lost. Scientists come to understand there is a trade-off between precision and richness as data are folded into categories. The error in this process also is quantified in mathematical terms and factored into all scientific findings. Mathematics helps scientists to break down data and put them back together into models.

Mathematics is the language used by scientists to model change in the world. Understanding change is a vital part of the inquiry process. Moreover, scientific advancement in all branches of science requires considered investment in the mathematical enterprise; good science and mathematics are complementary. Quality mathematics and science teaching requires teachers to compile, synthesize, evaluate, produce, and disseminate scientific information and models. This is foundational to initiating and guiding scientific inquiry. The ability to conduct this kind of instruction is significantly increased with a strong background in both science and mathematics. In a quality teacher education program, students should have opportunities to learn about the interrelationship between science and mathematics. This experience would be one mark of distinction.

Computational Biology Exemplar

Computational biology represents an important exemplar of where science and mathematics connect to produce significant advances to the scientific literature. Moreover, the modeling and mathematical advances in this interdisciplinary approach—often referred to as computational biology or bioinformatics—are powerful problem-solving tools (for more information, see the BioTech Web site at http://biotech.icmb.utexas.edu/pages/bioinfo.html). Even before the completion of the Human Genome Project, biologists posted the DNA sequence of their newly cloned genes into computerized databases to both organize and store the information and explore the function of their genes by comparing their sequence to similar gene sequences posted by other biologists. Genomics projects have profoundly reorganized our understanding of taxonomic relationships between organisms. The processes by which we come to understand these relationships routinely involve cladistic methods and molecular systematics that would not be possible outside of a digital world.

A decade ago it may have been possible to obtain a Ph.D. with the cloning of a single gene and publication of its sequence in a peer-reviewed journal. Today, cloning a gene is so elementary it can be accomplished using a kit purchased from a scientific supply house and is being done in many high schools across the country. High school students are able to write up these results and submit the gene sequences to the proper digital databases. The call by Newmann et al. (1995) for students to engage disciplinary content and methods including communication characteristic of the discipline, while situated in a problem-solving effort that extends beyond the classroom and for audiences beyond the school, is now possible in biology. Moreover, this possibility is richly enhanced because of digital technology. It is now possible for high school students to move beyond the mere rote learning of science facts. They can now combine the learning of scientific theory, historical facts, and cutting edge experimentation. This represents a significant advance in the teaching and learning process. This example from biology strongly suggests the need for teacher education programs that engage the nexus of biology and digital advancements. Biotechnology has many examples that can inform teacher education.

Some teachers may immediately picture a micropipetter or agar plates of bacterial colonies when they hear the term *biotechnology*. It is important that teachers and teacher educators understand how broad this term can be and how it has changed since the completion of the Human Genome Project and other genome sequencing endeavors. Just 10 years ago, the term *biotechnology* was more or less synonymous with the phrase *DNA science*. DNA science involves understanding the manipulation of DNA using enzymes, microbes, and other genetic engineering techniques for the purposes of basic scientific knowledge, the investigation and treatment of human health problems, or the development of new crops and environmental or agricultural products. Recently, biotechnology has also come to encompass the field of bioinformatics, which involves the collection, classification, and dissemination of genetic knowledge. This expansion in what counts as biotechnology is important for science and math teachers to know as they prepare students for their roles as modern citizens, scientific workers, and postsecondary students. Biotechnology is part of a broader digital transformation of science in which mathematics is foundational.

Engineer Exemplar

Engineering represents a second exemplar where science and mathematics have connected to produce significant advances to technologies involving images, video, audio, and more generally the world of communication and information technology. The ability to convert physical quantities such as gene sequences to numbers or digits has not only revolutionized biology but also influenced other disciplines including engineering and the study of phenomena such as sound waves, light intensity, and voltage. For engineers, changing analog quantities to digits has numerous advantages:

> Numbers are much less sensitive to physical problems associated with physical properties of the device used to store or manipulate them.
> Numbers require less storage space than the equivalent physical quantity of the phenomena.
> Numbers can be transported through space, using electronic, optical, or acoustic means (see Orsak et al., 2004).

Advances in software development and curriculum design open the world of engineering and digital signal processing and other advances in media technology including music, animation, communications, and networking to high school students with a background in Algebra II and a laboratory science course (Tate & Johnson, 1999; see also the Infinity Project Web site at http://www.infinity-project.org). The advances in engineering curriculum design are significant. The complexities of digital signal processing were once the province of graduate students in engineering or applied mathematics. Today, a high school student with minimal mathematics background can begin to learn digital signal processing concepts and engineering design. Some states are calling for engineering teacher certification and others have listed course work for students. For example, in the state of Texas, the course Multimedia and Information Engineering is part of an emerging portfolio of engineering and technology courses listed as part of the secondary curriculum offerings. A certified secondary mathematics or science teacher is designated to teach this course. If school districts are to offer this course, they will need to recruit teachers with a background in digital signal processing and multimedia engineering or provide professional development for teachers. A serious challenge will be supplying sufficient teachers with the skills and understandings to support the implementation of a high school engineering experience for minimally qualified students. Many schools offer engineering courses within magnet school structures or programs for gifted students. Yet it is feasible today, with more rigorous high school graduate requirements for all students in place, to offer engineering outside the boundaries of specialty programs such as gifted education. The challenge is largely a human resource development problem. Teacher education is an important remedy to this problem.

WHERE DO YOU START?

Secondary teacher education programs across the country vary in size and capacity. Definitive recommendations for beginning points are difficult to delineate; however, a few design features are worthy of additional discussion. Universities and colleges of various sizes and levels of resources offer undergraduate science and mathematics majors research opportunities. The competition for these opportunities varies dramatically. However, this is a great place to start building new opportunities for secondary majors interested in teaching biology, engineering, mathematics, or other scientific fields.

The rationale for the research experience is simple. The research provides prospective teachers the credibility and experience needed to integrate discipline-based content and real data into the mathematics and science curriculum (Committee for Economic Development, 2003). Often, students begin undergraduate research experiences in their freshman year of study. Today, it would be the rare case indeed to find a secondary education certification program for science educators that does not have a field experience requirement in a classroom. Perhaps in the future these secondary science and mathematics certification candidates should have a research experience as well. The Maryland Educator's Summer Research Program is an example of a public-private partnership that provides preservice and inservice teachers opportunities to work in academic, government, and industrial lab environments (Committee for Economic Development, 2003). Some universities or colleges have an office of undergraduate research (see, e.g., the Washington University Office of Undergraduate Research Web site at http://ur.wustl.edu). This type of administrative home could serve as a starting point.

Most prospective mathematics and science teacher education majors have a significant number of course requirements in their disciplinary field. To build truly distinctive programming will require teacher education faculty to establish learning alliances with engineering, science, mathematics, and computer science colleagues on their campus. For example, prospective secondary mathematics and science teachers might require an engineering experience within the teacher education program. This requirement could vary depending on the intellectual resources of the college or university and the nature of the learning alliance with colleagues in engineering and computer science. However, some experience in engineering design and digitizing the world around us would be a great start (Marven & Ewers, 1996; McClellan, Schafer, & Yoder, 1998; Orsak et al., 2002). It is important to note that engineering education programs are beginning to emerge across the country. For instance, the Department of Engineering Education at Purdue University is in its nascent stages; future plans include graduate degrees for students studying the science of learning and other topics in engineering education and an engineering teaching certification program for high school teachers (for more information, see http://www.engineering.purdue.edu/ENE/About). Moreover, the graduate program could serve as a source for future teacher educators and the undergraduate program as a model for preparing mathematics and science teachers with a strong engineering preparation. Other programs focus on practicing teachers. The Southern Methodist University School of Engineering has initiated an ambitious professional development strategy named Project Infinity. The goal is to prepare inservice teachers of mathematics and science to incorporate engineering into the secondary curriculum. The Purdue University and Southern Methodist University efforts are worthy of close examination by teacher educators.

In addition, integrating biological and digital experiences into education course requirements for certification could build on the student research experience and course work in the disciplines. The professional development model created at Southern Methodist University's Infinity Project, the University of Michigan's Center for Highly Interactive Computing in Education, and Washington University's Genome Sequencing Center Outreach program provide resources and tools to support a rich integration process. These resources help make the interrelationship between mathematics and science transparent.

A final component of the teacher education experience is vitally important. Student teaching field placement experiences are powerful learning opportunities. School district and university partnerships supporting the design features and exemplars outlined in this article would be essential to a fully articulated program of study for prospective secondary teachers. Specifically, it is important that teachers be placed in settings where educators are attempting to implement a school mathematics and science program that takes seriously the connections between mathematics and science, such as modeling and digital advances in biotechnology and engineering. Because many schools do not have classrooms that would support the ideas discussed in this article, it would be required in many cases to begin the development of supportive classroom learning experiences. This is not a trivial matter and represents a serious challenge. However, positive inroads toward this goal would not only strengthen teacher education but also positively influence scientific education in schools directly.

Your Signature Please

One important purpose of a signature is to function as a security service. A related security function is referred to as *nonrepudiation*, which is concerned with providing evidence to a third party (e.g., a judge or jury) that a party participated in a transaction. The signature marks of teacher education for prospective science and mathematics teachers should have a nonrepudiation function. That is, teacher education programming should produce teachers who have learning opportunities that allow them to experience the interrelationships between science and mathematics and that foster knowledge and understanding of biological, digital, and engineering advances. This would serve as a distinctive mark of quality. It would not be difficult to identify the teachers who are products of such programming.

The argument for a distinctive scientific signature in teacher education is consistent with science and mathematics education reformers who have called for an authentic approach to scientific instruction and learning that allows students to solve real problems, conduct advanced investigations, gather and analyze their own data, and publicly report their findings (American Association for the Advancement of Science, 1993; National Council of Teachers of Mathematics, 2000; National Research Council, 1996). The quality of teacher education is associated with its distinctive markings. Are you ready to sign on?

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