Grand Challenges and Opportunities in Mathematics Education Research

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Mathematics education researchers seek answers to important questions that will ultimately result in the enhancement of mathematics teaching, learning, curriculum, and assessment, working toward "ensuring that all students attain mathematics proficiency and increasing the numbers of students from all racial, ethnic, gender, and socioeconomic groups who attain the highest levels of mathematics achievement" (National Council of Teachers of Mathematics [NCTM], 2014, p. 61). Although mathematics education is a relatively young field, researchers have made significant progress in advancing the discipline. As Ellerton (2014) explained in her *JRME* editorial, our field is like a growing tree, stable and strong in its roots yet becoming more vast and diverse because of a number of factors. Such growth begs these questions: Is our research solving significant problems? How do we create a system and infrastructure that will provide an opportunity to accumulate professional knowledge that is storable and shareable as we work together to address significant problems (Hiebert, Gallimore, & Stigler, 2002)? How do we "facilitate research and development that is coordinated, integrated, and accumulated" (Lesh et al., 2014, p. 167)?

Other fields have raised similar questions and identified a list of *Grand Challenges* as a way to prioritize the most pressing problems that research should address. For example, the National Academy of Engineering of the National Academies recently released a list of 14 Grand Challenges that, if solved, could significantly change the lives of citizens around the world (National Academy of Engineering of the National Academies, 2008). The list includes challenges such as making solar energy economical, engineering better medicines, and preventing nuclear terror. There are 16 Grand Challenges listed for the global health field

(Omenn, 2006), eight for chemistry (National Research Council [NRC], 2005), eight for the environmental sciences (NRC, 2001), and eight developmental challenges from the United Nations (Omenn, 2006).

During the 2014 National Council of Teachers of Mathematics (NCTM) Research Conference, representatives from the NCTM Research Committee and the Special Interest Group for Research in Mathematics Education (SIG/RME) Executive Board met with representatives from the Directorate for Education and Human Resources at the National Science Foundation (NSF) to have an informal conversation about research in mathematics education. During that conversation, we learned that many fields have created lists of Grand Challenges, which are available to funding agencies as they prioritize funding efforts in those disciplines. We began to ask: If the field of mathematics education were to identify a short list of Grand Challenges, what might the list include? How could we initiate a process to generate that list?

That stimulating discussion was the impetus for this article in which we intend to begin a dialogue among mathematics education researchers and other stakeholders regarding the Grand Challenges and opportunities of our field. We commence with a description of the history of Grand Challenges and how they have provided a stimulus for advances in other fields. We include examples of Grand Challenges from other fields to demonstrate different ways in which they can be written as well as to describe the difference between Grand Challenges and research agendas. The next part of the article describes the results of a survey that the Research Committee distributed via multiple electronic mailing lists. In this survey, we solicited feedback about the characteristics of Grand Challenges for mathematics education as well as the types of challenges that educators think we currently face. The survey results led us to create a hypothetical Grand Challenge, which we present only as an example to illustrate the criteria that a Grand Challenge in mathematics education might satisfy. Drawing on the experiences of other fields, we conclude with a proposed process for generating Grand Challenges for mathematics education. We discuss why this effort is significant and why members of the mathematics education field should pursue it while also recognizing associated risks and moral obligations.

History of Grand Challenges

When David Hilbert presented his set of problems before the International Congress of Mathematicians in Paris in 1900, he hoped that they would spark discussion and discovery. He likely had no idea how influential his list would become in the development of mathematics over the next century and beyond (Yandell, 2002). Hilbert's (1902) list pulled together a set of unanswered (and sometimes unasked) questions that helped propel the field of mathematics. Hilbert recognized that mathematics in 1900 was at a crossroads and that having a sense of direction for the future was essential. He stated:

> If we would obtain an idea of the probable development of mathematical knowledge in the immediate future, we must let the unsettled questions pass before our minds and look over the problems which the science of today sets and whose solution we expect from the future. To such a review of problems the present day, lying at the meeting of the centuries, seems to me well adapted. For the close of a great epoch not only invites us to look back into the past but also directs our thoughts to the unknown future. (Hilbert, 1902, p. 437)

Hilbert (1902) acknowledged that it was difficult to know how important a problem would be in advance but that a good problem is one that is easy to understand yet "difficult in order to entice" the mathematicians to explore it (p. 438). He also understood the importance of a community of scholars being able to determine when a problem is solved, the need to develop new representations to express a problem, and the ability to explain its solution. He noted that "a new problem . . . is like a young twig, which thrives and bears fruit only when it is grafted carefully and in accordance with strict horticultural rules upon the old stem, the established achievements of our mathematical science" (Hilbert, 1902, p. 441). Not surprisingly, when Hilbert approached the task of creating the list, he drew on a particular epistemology, which in some ways called attention to some kinds of mathematics while possibly excluding others. We revisit this important idea below because it has implications for the process we propose in creating the Grand Challenges in the field of mathematics education. Although many of Hilbert's problems have been solved in whole or in part, some of them have raised new questions and sparked new lists of problems (e.g., the Millennium Prize Problems from the Clay Mathematics Institute, found at http://www.claymath.org/millennium-problems/millennium-prize-problems).

Perhaps even more significant than the mark Hilbert left in the mathematics community is the impetus his list of questions provided in other disciplines. The process of identifying challenging questions in mathematics prompted other fields to contemplate the biggest questions, or Grand Challenges, in their disciplines. Many other scientific and sociological fields have undertaken similar lists of Grand Challenges as a way to channel energy toward solving significant and relevant problems that can change the world. Following Hilbert's original design, Grand Challenges can identify easily understood problems of high priority, be measureable to gauge progress and indicate completion, and connect future needs to current foundations. These calls to action, as well as those in dozens of other fields, have rallied researchers, given direction to funding agencies, and helped shape priorities in critical-need areas. As various fields convened to create their lists, the criteria for what counts as a Grand Challenge differed to a great extent. In Table 1, we present Grand Challenges from a variety of fields to illustrate their diversity in scope and characteristics across disciplines.

The examples provided in Table 1 illustrate that the specificity of challenges differs across disciplines. The challenge might be as broad as shifting incentives to *encourage education research on the real problems of practice* (see Science Education, Table 1) or as specific as *create effective single-dose vaccines that can be used soon after birth* (see Global Health, Table 1).

Table 1
Examples of Grand Challenges From Other Disciplines

Discipline and Source	Grand Challenge
Mathematics Jackson (2000)	“Every nontrivial zero of the Riemann zeta function has real part equal to 1/2.” (p. 878) (This was also one of Hilbert’s problems.)
Geographic Information Science Gould (2010)	“How to promote sustainability: Where and how will 10 billion people live? How will we sustainably feed everyone in the coming decade and beyond? How does where we live affect our health?” (p. 65)
Engineering National Academy of Engineering of the National Academies (2008)	“Make solar energy economical.” (para. 1)
Environmental Science National Research Council (2001)	“Understand the regulation and functional consequences of biological diversity, and to develop approaches for sustaining this diversity and the ecosystem functioning that depends on it.” (p. 20)
Chemistry National Research Council (2005)	“Lead the way in the development of future fuel alternatives derived from renewable sources such as biomass as well as landfill gas, wind, solar heating, and photovoltaic technology.” (p. 7)
Global Health Varmus, Klausner, Zerhouni, Acharya, Daar, and Singer (2003)	“Create effective single-dose vaccines that can be used soon after birth.” (p. 398)
Science Education Alberts (2013)	“Shift incentives to encourage education research on the real problems of practice as they exist in school settings.” (p. 249)

These examples also illustrate how the structure of Grand Challenges differs from research questions. The wording of the challenge typically has the solution embedded within the statement of the problem. For example, *make solar energy* *economical* (see Engineering, Table 1) is a statement of the outcome of research but does not specify a research question, perspective, or methodology. In this way, Grand Challenges differ from other documents that list research priorities that do not necessarily have an outcome in mind a priori.

Additionally, the methods by which disciplines created these lists of Grand Challenges are just as diverse. Researchers within science education solicited articles that list Grand Challenges from a variety of important leaders in the field. Their manuscripts were published in a special issue of *Science* (Grand Challenges in Science Education, 2013) to be read and debated by researchers. Other disciplines, supported by the National Research Council or other organizations, held conferences to initiate discussion on their Grand Challenges with a committee of members of the field completing the work.

With so many different examples to draw from, we as members of the mathematics education field have to decide how specific to make our challenges and the consequences of that choice. We need to consider how we define Grand Challenges, what impact we hope they have on our work, what processes we will use to create the list, and what we risk by prioritizing a list of challenges. We begin a conversation on these issues in the following sections.

What Are Potential Grand Challenges for Mathematics Education?

In considering how to define a Grand Challenge, the NCTM Research Committee first read Omenn's (2006) and Gould's (2010) discussions of Grand Challenges. We then distributed a survey to the NCTM membership and the electronic mailing lists of the National Council of Supervisors of Mathematics (NCSM), the Association of State Supervisors of Mathematics (ASSM), the American Educational Research Association's SIG/RME, and the Urban Mathematics Leadership Network in June 2014. Although not all stakeholders were involved in this initial solicitation, it was our first attempt to engage members of the community for feedback about Grand Challenges. Through the survey, we asked respondents to make suggested improvements to the five criteria outlined by Gould (2010) and to propose Grand Challenges that mathematics educators need to solve. Based on respondent feedback, we offer a revised set of criteria for Grand Challenges in mathematics education in Figure 1.

The proposed revisions to Gould's (2010) characteristics were made based on three ideas represented in survey responses. The first criterion originally stated that a grand challenge should be "doable." Some respondents suggested that we would need to define what it means for a Grand Challenge to be "doable" while also recognizing real-world factors such as time constraints, the inclusion of mathematics teachers in research, and perseverance. Second, respondents highlighted the need for any criteria to reflect the role of diversity and equity. Finally, Gould's fourth criterion originally stated that researchers should be able to use well-defined metrics for determining the completion of a project. Survey respondents critiqued the phrase "well-defined metric" used by Gould, commenting that existing metrics are often unavailable and would need to be developed to meet and communicate about each challenge.

Grand Challenges:

1. Represent complex and extremely difficult questions that are solvable (potentially within 10–20 years);
2. Improve the quality of life through positive educational, social, and economic outcomes potentially affecting millions of people;
3. Involve multiple research projects across many sub-disciplines to be satisfactorily addressed;
4. Require measureable outcomes so that progress and completion can be identified;
5. Compel popular support by encouraging the public to relate to, understand, and appreciate the outcomes of the effort.

Figure 1. Proposed criteria for Grand Challenges in mathematics education.

Possible Grand Challenges for Mathematics Education

In response to the survey question about proposed Grand Challenges for the mathematics education community, three specific themes emerged from the responses:

- Changing perceptions about what it means to do mathematics.
- Changing the public's perception about the role of mathematics in society.
- Achieving equity in mathematics education.

Respondents alluded to the challenge of helping people see that doing mathematics is about problem solving, reasoning, curiosity, and enjoyment, and not about following procedures to get "the answer" or just about doing well on a test. Another related theme was changing the image of or public perception about mathematics. How can we support the public in more deeply understanding the role of mathematics in society? By what means can we address common thinking such as "I was never good at math"? Survey participants mentioned the need to see mathematics as something that human beings normally do and that has relevance and beauty.

The third theme to emerge from respondent data concerns the importance of equity. Comments pointed to an awareness of the relationship between equity and teaching as more complex than "just" achievement gaps among different groups of students. Participants referred to value issues in terms of which content and approaches and whose ideas get recognized, general beliefs about who can do mathematics and how these beliefs affect teaching and learning, the role assessments play (or could play) in challenging inequity, and how we really teach and prepare teachers to teach within a social justice frame of mind.

Several of the survey respondents indicated implications for teaching along the lines of the three ideas we highlight. Responses showed concern for the need to have curricula and teaching approaches that reflect today's world (e.g., in terms of technological advancements) and its language and cultural diversity. Respondents also mentioned the need to examine the purpose of teaching mathematics in school. Is mathematics for further study of mathematics, for college, for everyday life, or for critical thinking? This examination could include looking at how teachers can facilitate and support students' development as independent thinkers while accounting for different careers, cultural practices, and common, everyday activities.

Although these three themes emerged from the responses of mathematics educators who replied to the survey, we realize that mathematics education in this country faces additional pressing problems. Our goal with this article is to acknowledge some of the pressing problems in mathematics education, as revealed by the three themes above, as well as initiate a discussion of other challenges. In the next section, we provide an example of a Grand Challenge that was motivated by the themes identified from the survey.

A Hypothetical Grand Challenge

What might a Grand Challenge look like in mathematics education? In this section, we offer a hypothetical example of a Grand Challenge that is based upon the suggestions of mathematics educators who answered the survey. Our example is only meant to illustrate how a Grand Challenge could satisfy the criteria listed in the previous section; we are not suggesting that it is necessarily a Grand Challenge we should pursue.

Hypothetical Grand Challenge: *All students will be mathematically literate by the completion of eighth grade.*

There is no question that reading literacy of adults in the United States has been the focus of the public's attention in the last few decades. Articles like *Newsweek's* "Why Johnny Can't Write" (Sheils, 1975) and books like *A Nation at Risk* (National Commission on Excellence in Education, 1983) focused the attention of the public on high illiteracy rates in the United States. Consequently, a tremendous amount of resources were poured into reading programs and schools to improve literacy. An intense public literacy campaign included the introduction of the show Reading Rainbow on public television and the distribution throughout schools and libraries of the American Library Association's READ posters, a promotion that was initiated in 1985 and featured famous actors urging children to read.

Attention to literacy continued with the passage of the *No Child Left Behind Act* in 2002. In that Act, Congress required that all U.S. children be able to read by third grade. This bold agenda, no matter the controversies surrounding it, had the effect of funneling significant resources toward reading initiatives. In particular, the U.S. government and other agencies provided funding for schools to prepare and equip teachers to implement research-based reading programs and for reading experts to conduct more research toward improving students' literacy. It is generally accepted that the inability to read serves as a severe disadvantage to participating fully as a U.S. citizen; therefore, this ambitious goal has received widespread public support.

Many mathematics education researchers have pointed out that for individuals to participate in our information-saturated world, they must become mathematically literate (Cobb, 1997; de Lange, 2003; Organisation for Economic Co-operation and Development [OECD], 2007, 2010). For example, being able to interpret the vast amount of statistical data presented by the media during election seasons is critical for making the best decision about the future direction of the country. Reasoning quantitatively about investments is critical for ensuring one's future financial security.

Although the need for creating mathematically literate citizens is rarely questioned by educators, there are different interpretations of the meaning of the term. Very simply, one might consider mathematical literacy as the ability to solve problems, reason about and analyze numerical information, and know the meaning of important mathematical vocabulary (Oxford Learning, 2010). A more detailed, oft-cited definition of mathematical literacy comes from the Programme for International Student Assessment (PISA) Report (OECD, 2007): "The capacity of students to analyse, reason and communicate effectively as they pose, solve and interpret mathematical problems in a variety of situations involving quantitative, spatial, probabilistic or other mathematical concepts" (p. 304). Further, Evans (2000) suggested that mathematical literacy is the "ability to process, interpret and communicate numerical, quantitative, spatial, statistical, even mathematical, information in ways that are appropriate for a variety of contexts and that will enable a typical member of the culture or subculture to participate effectively in activities that they value" (p. 236). Although these definitions differ, they share the idea that being mathematically literate involves being proficient at more than basic computations. Such literacy includes knowledge of how to interpret quantitative information in realistic contexts and make judgments based upon mathematically sound analyses of the world around us.

Reading literacy has enjoyed the spotlight in the last few decades, and deservedly so; but perhaps it is time for mathematical literacy to garner equal public attention and support. Therefore, a possible Grand Challenge could be that all students become mathematically literate by the completion of eighth grade. We do not suggest an earlier grade level, because of the critical mathematics concepts that students develop in the middle grades. By eighth grade, students should learn whole number, rational number, and statistics concepts necessary for participating more fully in society, improving their personal lives, and establishing the foundation for success in mathematics in future academic pursuits.

We chose this hypothetical Grand Challenge merely to illustrate how a Grand Challenge can satisfy the revised criteria we listed above. Ensuring every eighth-grade graduate will be mathematically literate would be extremely challenging, requiring not only financial support from funding agencies that the reading initiative garnered but also wide public support. Yet, this challenge is doable and when accomplished would create millions of citizens who can make more informed decisions based upon mathematical reasoning. Individuals would be able to analyze information and make better decisions about the future and quality of their own lives as well as the direction of the country. If all students are to become mathematically literate, it would require the coordinated efforts of researchers and practitioners from a multitude of disciplines including, but not limited to, mathematics education researchers and educators (especially those who specialize in equity), mathematicians, special educators, psychometricians, and cognitive psychologists. We would need to identify and potentially develop well-defined metrics to measure progress toward accomplishing this Grand Challenge and ultimately its completion. We would also need a coordinated strategy and infrastructure to garner support and energize the public toward solving this Grand Challenge.

What Process Might We Use to Draft Grand Challenges?

Different fields have used a variety of processes to identify and draft Grand Challenges (e.g., using a committee approach versus assigning the task of writing a challenge related to a specific topic to one individual). In reviewing the related literature, it is clear that creating a list of Grand Challenges is a difficult and perhaps daunting task. How should we determine priorities? Who should be engaged in this conversation? Who will write initial drafts? How do we build consensus? What are the potential benefits, risks, and moral issues associated with this process? In addition to gaining insights from other fields, we can also learn from earlier efforts within mathematics education. For example, members of NCTM (2012) convened a group in 2008 and sought input from the community that resulted in the conference report *Linking Research & Practice* (Arbaugh et al., 2010). That effort identified "questions of importance to the practitioner community" (p. 6) and can inform the discussion of Grand Challenges in mathematics education.

We propose a process and invite you to provide ideas about the proposed process. Rather than delegating this task to a small committee of researchers, we suggest a process that attempts to engage as many voices as possible. Many of you have shared your expertise and ideas by participating in the NCTM Research Committee's survey on what constitutes a Grand Challenge in our field. We consider this article an open invitation to all readers to join us in the process of cocreating the Grand Challenges for mathematics education. As we move forward with this effort, you would have opportunities to help draft Grand Challenges, comment on drafts written by others, and engage in conversations online or at conferences and professional meetings. It is clear to us that people's theoretical orientations, ideologies, epistemologies, and values will shape what they might put forward. Part of the reason for involving stakeholders across different communities (rather than just forming a committee) is to avoid singular epistemologies, values, and ideologies in doing this work (i.e., Hilbert's approach).

Although the NCTM Research Committee will spearhead this effort, we seek to engage as many people as possible, including researchers, mathematicians, mathematics educators, teachers, other school personnel (e.g., mathematics coaches, curriculum coordinators, and administrators), curriculum developers, and policy makers. Widespread participation is vital to the success of this effort. To this end, we will host a session at the 2015 NCTM Research Conference and 2015 NCTM Annual Meeting to seek input about the process, the criteria, and the content of Grand Challenges, and to engage in a meaningful discussion about the future of this endeavor. We expect that these conversations will also take place in other formal and informal venues, including possible working sessions at the annual meetings of the American Educational Research Association (AERA), American Mathematical Association of Two-Year Colleges (AMATYC), Association of Mathematics Teacher Educators (AMTE), the Benjamin Banneker Association, Educators of Native American Students (EONAS), Mathematical Association of America (MAA), National Council of Supervisors of Mathematics (NCSM), North American Chapter of the International Group for the Psychology of Mathematics Education (PME-NA), TODOS: Mathematics for All, Women and Mathematics Education (WME), and regional NCTM meetings. We plan to provide online discussion venues for those who are not able to attend more formal meetings. From these initial discussions, it will be critical to document ideas and concerns as we develop a strategic plan for guiding future work.

The next stage will involve drafting Grand Challenges and the rationale for them (i.e., how they meet the criteria of a Grand Challenge and why they should be prioritized). The NCTM Research Committee will write an open invitation for individuals or groups to submit Grand Challenges. The NCTM Research Committee will also convene a diverse group with a wide variety of expertise to review all submitted challenges, write additional challenges, vet them according to the criteria set forth in the invitation, and provide opportunities for the field to comment on them. To facilitate this work, the NCTM Research Committee will work with the NCTM Board to identify and solicit funding to convene stakeholders.

Moral Obligations to Consider Throughout the Process

Any time a representative group of people is given an opportunity to identify Grand Challenges for an entire field, there is a moral obligation to consider the associated risks and weigh them against the potential benefits. The risks associated with creating a document that identifies our field's Grand Challenges could be significant, yet we hope to minimize the risks by acknowledging and addressing them throughout the process. In the NCTM Research Committee's discussions about these Grand Challenges, we have talked about personal and professional challenges that people in our field could endure as a result of such a document. We include just a few examples here and hope that they spur further discussion so we better understand the impact of such a document.

A document identifying the Grand Challenges is a values statement. That is, by identifying some areas as Grand Challenges, we draw attention to certain areas and leave others unmentioned. The result of such valuing could have an impact on people personally; they may feel as if the field does not care about the work that they find interesting and important. It could also have an impact on people professionally. For example, many of us have served on promotion and tenure committees at our institutions and can imagine how such a document could be misused by people making decisions about raises, about what one writes in an external review letter, and about who is granted promotion and tenure. We also imagine that such a document could guide funding agencies to support what the experts in the field see as the most important priorities.

Another risk is that the Grand Challenges could be misappropriated. For example, if a Grand Challenge targets issues related to equity, how do we word it so that important groups are not left out? Moreover, the wording may suggest directions for resource allocation toward achieving these Grand Challenges and could have serious implications for teachers and students with whom we work.

As pointed out by the report from the Grand Challenges Canada group (2011), as well as Winter and Butler's (2011) discussion examining Grand Challenges in the information systems field, another risk is that there is no guarantee of success. Some identified challenges or problems may take years to study and others may simply not be achieved. Avoiding the challenge, however, is not the solution. As we move forward, we acknowledge that there are no guarantees and position ourselves to increase the likelihood of success.

Why Pursue This Effort?

Given these risks, why should we pursue this initiative? Working together not only to initiate a list of Grand Challenges in mathematics education but also to address them through research and policy is an opportunity we cannot relinquish. Currently, people outside of education are setting agendas about what is valued and what might get funded. In the process, our voices have not always been heard in some political and economic arenas. If we do not set forth an agenda as a community, others certainly will. What could we accomplish from this Grand Challenges Initiative? This effort could:

- Spark discussion and discovery;
- Rally researchers;
- Influence funding for research;
- Establish a national campaign (similar to efforts in reading);
- Help shape priorities in critical-need areas;
- Facilitate collaboration among researchers and practitioners;
- Build a knowledge base that is storable, shareable, and cumulative (Hiebert et al., 2002);
- Facilitate collaboration across fields;
- Influence policy and public opinion; and
- Secure resources to establish infrastructure that supports research efforts over time.

This initiative also means capitalizing on the diversity of research programs that draw on a variety of epistemologies. The process outlined here will involve multiple discussions and other venues for gathering information to try to represent some of the enduring and solvable Grand Challenges facing our field. We hope you will contribute in our future discussions.

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