Increasing the Number of U.S. STEM Graduates:

Insights from the STEM Education Modeling Project

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Foreword

This paper presents insights from developing and testing a system dynamics model of the U.S. STEM education system (the "U.S. STEM Education Model") developed by Raytheon Company and donated to the Business-Higher Education Forum (BHEF) in July 2009. The model, which is free and available in open source for use by the public through www.stemnetwork.org, is being managed by a partnership among BHEF, Raytheon and The Ohio State University's (OSU) Battelle Center for Mathematics and Science Education Policy.

The U.S. STEM Education Model is part of BHEF's STEM Education Modeling Project, which is designed to help increase the number of students who pursue majors and careers in the fields of science, technology, engineering, and mathematics (the disciplines collectively known as STEM). The project's impetus is BHEF's STEM Initiative, launched in 2005 with the goal of doubling by 2015 the number of U.S. students who graduate in STEM fields.

This paper is the result of years of effort on behalf of BHEF and several of its members. None of this work would be possible without William H. Swanson, Chairman and CEO, Raytheon Company and BHEF Vice Chair, who provided the intellectual leadership for the U.S. STEM Education Model and committed thousands of hours of time from a team of Raytheon engineers led by Brian Wells and H. Alex Sanchez. BHEF's STEM Working Group (Appendix A), under the leadership of Swanson and California Polytechnic State University President Warren Baker, has provided ongoing strategic guidance.

At the direction of OSU President Gordon Gee, OSU faculty members Kathryn Sullivan and Joseph Fiksel have been instrumental in managing the model and advancing its use. With the support of ACT CEO Richard Ferguson, staff members James Sconing and Steve Robbins led a team of ACT researchers who prepared specialized data sets for the model. Boeing Senior Vice President for Human Resources and Administration Richard Stephens supported the involvement of staff members Mike Richey, Paul Newton, and Mohammad Mojtahedzadeh in developing a user interface for the model, and Arizona State University President Michael Crow has supported the involvement of faculty member James Middleton.

In addition to these numerous in-kind contributions, the STEM Education Modeling Project has benefited from generous financial backing. The Bill & Melinda Gates Foundation has supported the advancement and use of the model since 2008, and with the support of Northrop Grumman Corporation President and CEO, Wes Bush, Northrop Grumman has provided funding to enhance the portions of the model that pertain to teachers. The Ewing Marion Kauffman Foundation hosted the inaugural convening of the STEM Research & Modeling Network (SRMN) in 2008. Bringing together researchers, policymakers, practitioners, corporations, and funders around the goal of using simulation modeling to improve STEM education and policy, the SRMN plays a central role in advancing the U.S. STEM Education Model. Feedback from SRMN members helped to shape the model and gave rise to some of the insights presented in this paper.

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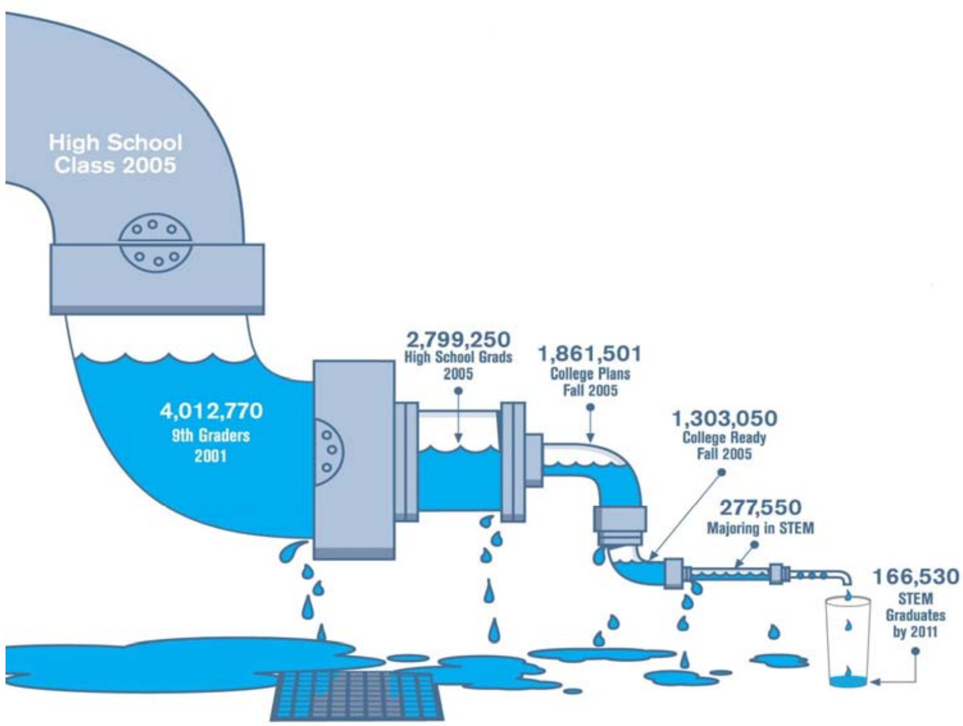
Science, technology, engineering, and mathematics (STEM) are vital to American competitiveness, yet relatively few students obtain a STEM bachelor's degree (Business-Higher Education Forum, 2005, 2007). As Figure 1 shows, in 2001 there were just over four million 9th graders in the United States. Slightly fewer than three million of those students graduated from high school four years later, and nearly 1.9 million attended two- or four-year colleges (National Center for Education Statistics, 2006). However, fewer than 300,000 selected STEM majors, and only about 167,000 are expected to earn STEM degrees by 2011 (National Science Board, 2008).

Figure 1. The U.S. STEM Education Pipeline



Source: NCES Digest of Education Statistics; Science & Engineering Indicators 2008
Graphic courtesy of Bill & Melinda Gates Foundation

This relative dearth of U.S. STEM graduates and the lack of adequate progress in stoking the pipeline led BHEF to launch its Securing America's Leadership in Science, Technology, Engineering, and Mathematics (STEM) Initiative in 2005, with the goal of doubling the number of U.S. STEM graduates by 2015. Given this set of constraints, William H. Swanson, Chairman and CEO, Raytheon Company and BHEF Vice Chair asked, "How can we determine which ideas are most likely to be effective in increasing the number of STEM graduates?" With this charge, BHEF's STEM Working Group sought mechanisms to:

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- Identify the highest leverage points and most strategic starting points.
- Ascertain the effect of scaling various policies and programs to a national level.
- Prioritize among many options to increase the number of STEM graduates.

Using System Dynamics to Meet the Challenge

In 2006, Raytheon's systems engineers took up these challenges as part of the company's Systems Engineering Technical Development Program. Through this program, teams of Raytheon engineers applied the methods of systems engineering, modeling, and simulation to examine the U.S. educational system.

System dynamics modeling is based on a high-level view of a system—referred to as a dynamic hypothesis—that is used to develop a conceptual understanding of the system. Each dynamic hypothesis includes causal feedback loops that connect different parts of the system; these feedback loops drive the overall behavior of the system.

Used widely in other fields, system dynamics modeling has long been helpful in studying complex topics such as the economy, climate change, and the spread of diseases. Although systems models have rarely been applied in education, lessons from other fields suggest that using this kind of analytical tool can help advance policy discussions by offering a more organized and comprehensive view of the multifaceted U.S. education system.

Some Benefits of System Dynamics Modeling

The use of system dynamics modeling in policy can:

- Depoliticize discussions of education improvement by using systemic outcomes (i.e., increasing the number of STEM graduates in the United States), rather than specific programs or policies, as a starting point.
- Demonstrate the capacity of the system to support the desired outcomes, often revealing unintended consequences in the process.
- Display the time lag between the implementation of a program or policy and the desired outcomes.
- Allow for examination of the relative cost associated with different policies.

In consultation with BHEF and other education experts, Raytheon engineers drew on national education, labor, and census datasets and conducted extensive reviews of educational research to construct the model. As a starting point, the Raytheon team focused on areas that the research indicated as the highest leverage points related to the specific challenge of increasing the number of students who pursue and earn STEM degrees: K-12 teachers, and undergraduate STEM persistence. Focusing initially on these two areas, they developed complex algorithms, a series of dynamic hypotheses, and more than 200 unique variables to simulate and assess the impact of various STEM education proposals on the number of STEM graduates.

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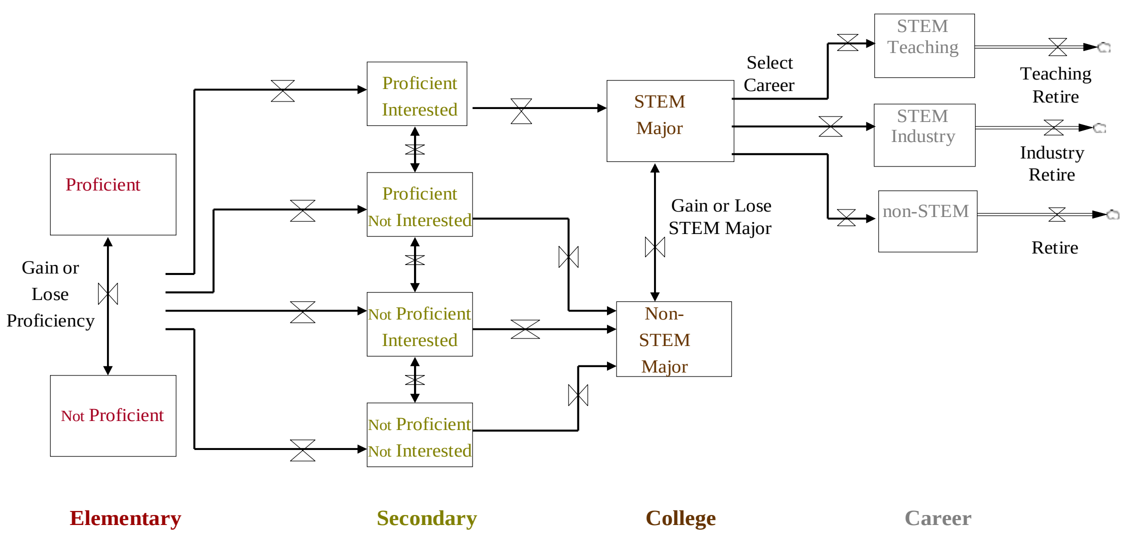
After three years and significant effort by Raytheon, the result is the U.S. STEM Education Model, which tracks the flow of student capabilities and interest in STEM as they move through the school system, into postsecondary education, and through their careers (Figure 2). In elementary school, students either are STEM proficient or not STEM proficient. NAEP mathematics scores serve as a proxy for STEM proficiency in the fourth grade. When students enter secondary school, the model divides into four streams based on mathematics proficiency and interest in STEM-related activities. After high school, any student who is not STEM-interested drops out of the model because the focus of the model is on the production of STEM graduates, and there is negligible flow into STEM majors. In addition, students who are not college ready (i.e., math proficient) also drop out of the model. Thus, the postsecondary portion of the model only includes students who declare STEM majors or STEM education majors. After college, the model divides into three streams: those who choose non-STEM careers, those who choose STEM industry careers, and those who choose STEM teaching careers.

Figure 2. Simplified Representation of the U.S. STEM Education Model



What Have We Learned?

The processes of defining the U.S. STEM education system and exploring what leads students to choose and persist in STEM majors have placed existing research in a new perspective. The development and vetting of the model have illuminated several points that are particularly relevant in the current federal and state policy contexts, and that can be crucial to increasing the number of STEM graduates.

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1. Student interest in STEM and proficiency in mathematics are the key determinants of choosing a STEM major.

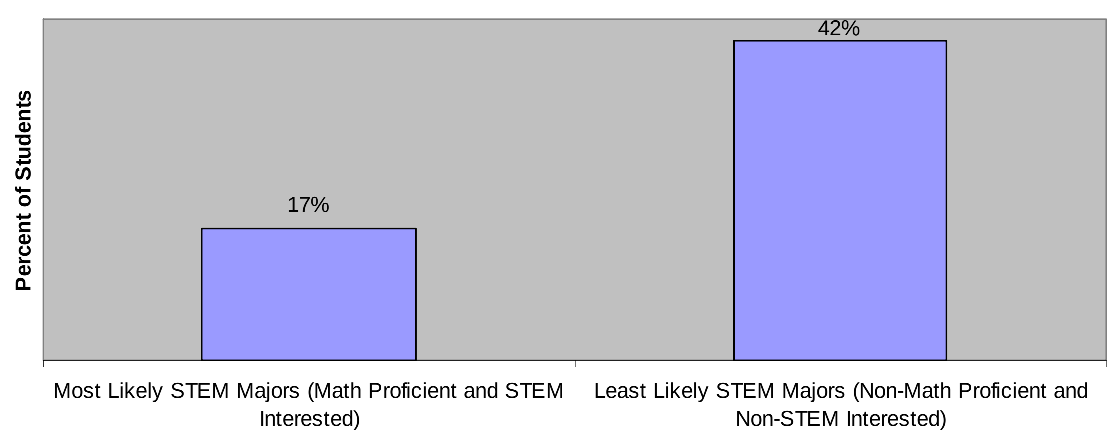
At a minimum, students will be admitted into STEM majors only if they are sufficiently proficient in mathematics, and they will select STEM majors only if they are interested in STEM or STEM teaching. For these reasons, the K-12 portion of the model sorts students into quadrants of high and low proficiency and high and low interest.

The secondary school segment of the model is structured around data related to mathematics proficiency (as defined by ACT college readiness cutoff scores) and interest in STEM-related activities (as defined by the ACT student interest inventory). These data, provided by BHEF member ACT, show that among males and females who took ACT assessments in grades 8, 10, and 12:

- Roughly 15 to 20 percent in each grade fall into the mathematics proficient-STEM-interested category, the most likely pool of candidates to pursue STEM majors and careers.
- The largest group—roughly 40 to 45 percent in each grade—falls into the non-math proficient-non-STEM-interested category, the least likely pool of candidates to pursue STEM majors and careers.

It is important to note that the 12^{th} grade students in the ACT sample are college bound, and as such are not nationally representative of all students. Figure 3 illustrates the proportions of 12^{th} graders from the ACT sample who are most likely to pursue STEM majors (math proficient and STEM-interested) and least likely to pursue STEM majors (not math proficient and not STEM-interested).

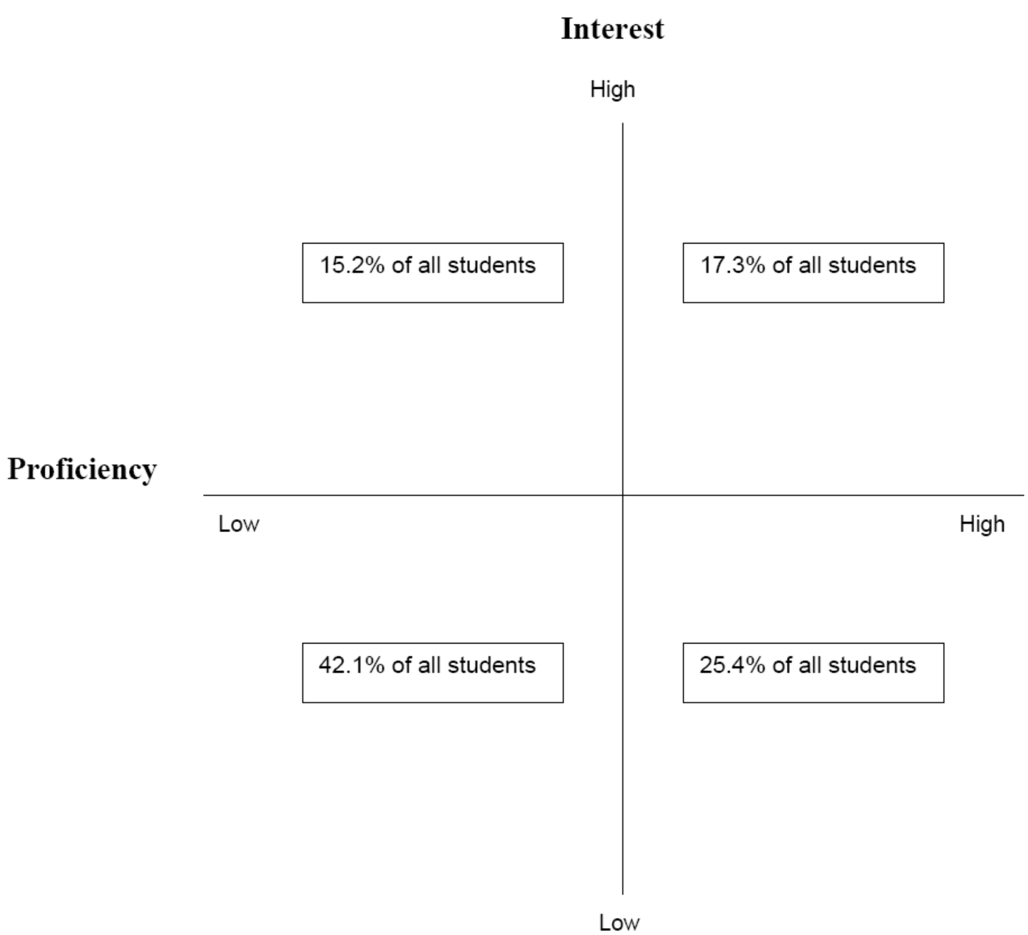
Figure 3. Proportions of 12th Grade ACT Test Takers Most and Least Likely to Pursue STEM Majors



Source: ACT, Inc., 2009

In light of these findings, and considering the time and resource constraints associated with doubling the number of STEM graduates by 2015, it is useful to identify whether interest or proficiency—or both—is the more strategic focus. As an example, looking at the distributions among the four quadrants of proficiency and interest for 12th graders (Figure 4), it appears that targeting STEM interest among math proficient students might be more fruitful in the short term because that group represents the largest proportion of 12th graders in the ACT sample who are likely to opt for STEM majors.

Figure 4. Distribution of STEM Interest and Mathematics Proficiency among 12th Graders



Source: ACT, Inc., 2009

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Further analysis of the ACT data provides additional support for focusing on interest:

- The proportion of math proficient students increases from grade 8 to grade 12, with seemingly greater gains for males than for females (Figure 5). Although the overall levels of proficiency in each grade are not satisfactory, many resources are being directed at proficiency, and the trend from grade 8 to grade 12 is in a positive direction for students in the sample.
- STEM interest, on the other hand, remains relatively stable from grade 8 to grade 10, and dips slightly for females in grade 12 (Figure 6).

Figure 5. Mathematics Proficiency in Grades 8, 10, and 12

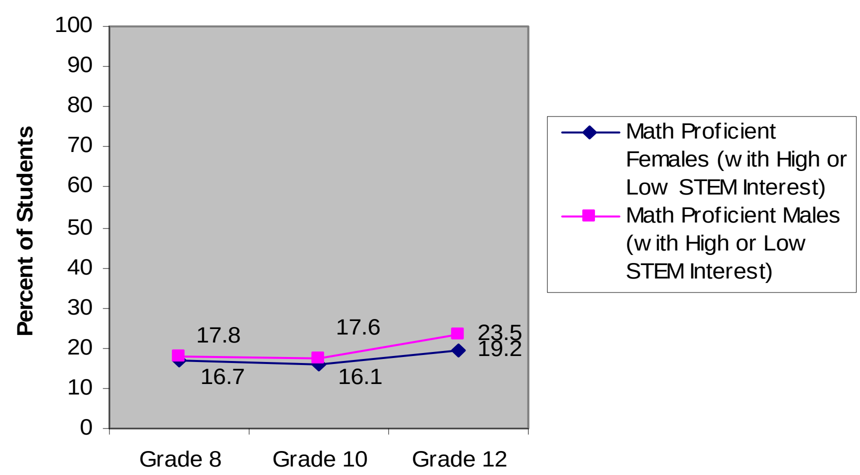
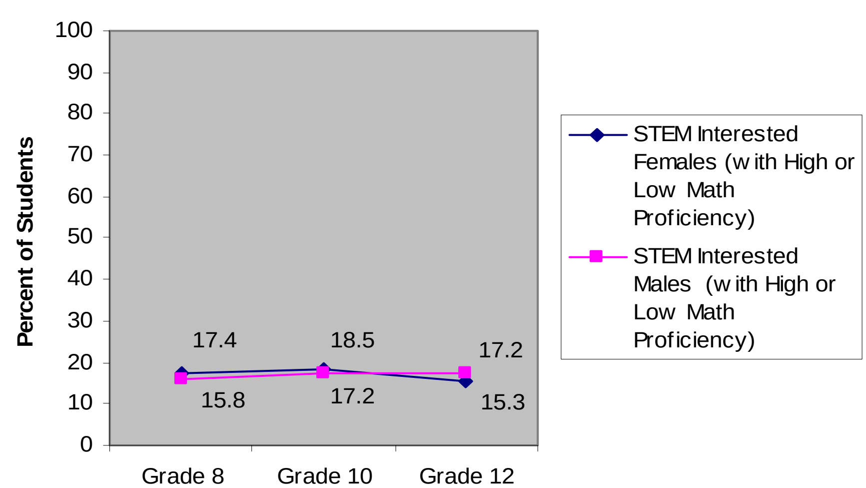


Figure 6. STEM Interest in Grades 8, 10, and 12



Source: ACT, Inc., 2009

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The low overall levels of STEM interest lend support to the considerable body of research stressing the importance of engaging students during the middle school years. Moreover, by highlighting a decline in interest for females between grades 10 and 12, these data suggest that it might also be productive to develop targeted interventions for high-school females to increase their interest in STEM.

2. STEM-capable teachers are vital to increasing STEM interest and mathematics proficiency.

Researchers are in wide agreement that teachers exert the greatest in-school influence on student learning. Accordingly, the K-12 portion of the U.S. STEM Education model reflects the importance of teachers, and is driven by value-added research on teachers' effectiveness in increasing students' mathematics proficiency (e.g., Gordon, Kane, & Staiger, 2006; Hanushek, 2002). Specifically, the model operates on two populations of teachers: STEM-capable and not STEM-capable, with STEM-capable teachers defined as those who improve students' average rank in mathematics proficiency.

The model's equations are built around two key findings related to teachers, derived from Hanushek (2002):

1. Teachers account for approximately 8.5 percent of the variation in student performance during elementary and high school.
2. Moving a student from a teacher in the 50th percentile to one in the 85th percentile increases the student's performance on standardized mathematics tests by seven percent in a given year.

Simulations run with the model suggest that high levels of attrition or skill development among the lowest performing teachers are required to double the numbers of math-proficient students who declare STEM majors. Specifically, as shown in Figure 7:

- Maintaining baseline attrition rates yields no growth in the number of math proficient high school graduates declaring a STEM major.
- Total attrition of teachers who are in the lowest decile after their third year of teaching results in a modest increase in the number of math proficient students.
- Total attrition of teachers who are in the lowest quartile after their third year of teaching (an unlikely measure) results in a dramatic increase in math proficient students.

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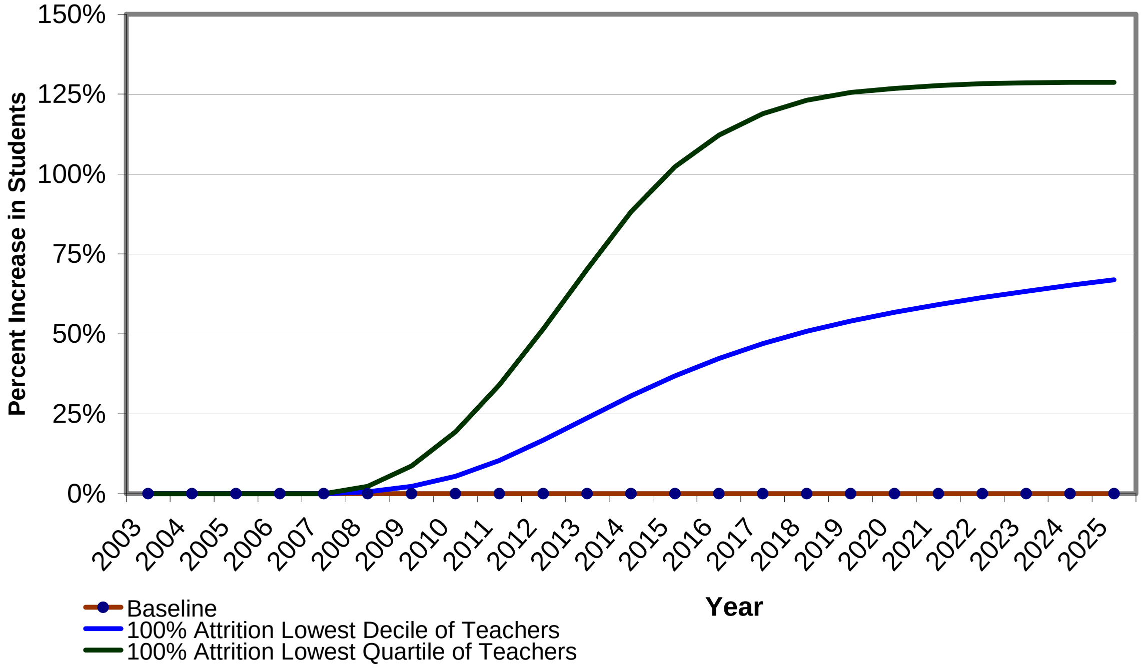
Figure 7. Effect of Non-STEM Capable Teacher Attrition on Math Proficient High School Graduates Declaring STEM Majors



On their own, these findings simply validate what the education community already knows from research and practice about the influence of teachers. Modeling the findings, however, is powerful for several reasons. First, the simulations quantify the effect of teachers on students' mathematics proficiency. Second, they provide a dramatic visual demonstration of that effect in a way that is intuitive to a wide range of audiences. Third, they illustrate the time lag between implementing programs to increase the proportion of STEM-capable teachers and the desired effect of increasing the number of math proficient students, which in Figure 7 is a decade or more. This type of illustration is a particularly useful decision-making tool when results must be achieved during a specified period of time (a political term, funding cycle, etc.). And finally, a graphic demonstration such as Figure 7 focuses attention on a goal (i.e., increasing the relative proportion of STEM-capable teachers) as opposed to a specific mechanism for achieving that goal (i.e., linking tenure to performance). In this manner, the model can depoliticize discussions of potentially contentious topics such as teacher tenure.

3. Focusing on undergraduate education yields an early and significant return on investment.

As discussed previously, about half of the first year students who declare STEM majors in their first year ultimately leave STEM undergraduate programs and do not earn STEM degrees. The first year of college is particularly important because 35 percent of STEM majors switch after their first year (Daempfle, 2002).

Many colleges and universities use bridge and cohort programs to promote first-year success. Bridge programs typically are offered in the summer between high school graduation and the first term of college, and typically are designed to hone students' academic skills and prepare

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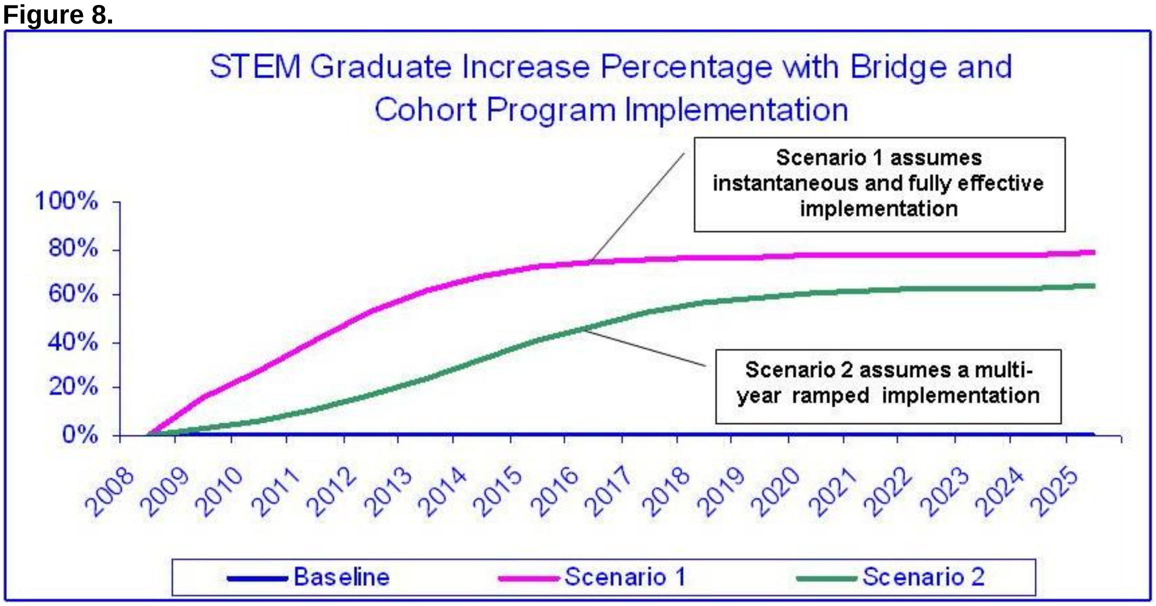
them for the transition to college. Cohort programs build strong social networks among students by grouping them together through their course sequence, affinity dorms, and other activities.

Both types of programs have been shown to increase persistence, largely because they foster student engagement and social interaction, leading to a greater sense of connection to their programs and universities (Springer, Stanne & Donovan, 1999; Tinto, 1993; Urban Institute, 2005). Cohort programs in particular have an important effect on the production of STEM graduates (Nestor-Baker & Kerkor, 2009), and they have a relatively low cost of implementation, which makes them an especially desirable option.

The undergraduate portion of the U.S. STEM Education Model reflects the importance of bridge and cohort programs to STEM persistence, and is driven by research on these programs (e.g., Gilmer, 2007; Stuart, 2007). Simulations run with the model show that a multi-year, ramped implementation of bridge and cohort programs would lead to a 40 percent increase in STEM graduates in 7 years, whereas instantaneous implementation (the extreme example of all colleges and universities implementing bridge and cohort programs immediately) yields a 72 percent increase in STEM graduates by 2015 (Figure 8).

Figure 8.



Multi-year, ramped implementation is the more plausible scenario for several reasons, including the relative costliness of bridge programs. Although this strategy does not double the number of STEM graduates, the simulations in Figure 8 show that focusing on undergraduate education has a more immediate impact on that goal than increasing the proportion of STEM-capable K-12 teachers (see Figure 7). This finding is particularly relevant in light of the predominant P-12 focus of many STEM programs and policies and the evolving national discussions of STEM education policy.

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4. Neither K-12 strategies nor postsecondary strategies alone are likely to double the number of STEM graduates by 2015.

As shown in Figure 8, simulations run with the model show that increasing the number of universities that offer bridge and cohort programs can yield substantial increases in the number of STEM graduates over time. Increasing the proportion of STEM-capable teachers in high school also has a noticeable effect—albeit smaller and more delayed—on the number of STEM graduates (see Figure 7). Although these two strategies are not related to each other, the model shows that only when they are implemented at the same time does the number of STEM graduates double by 2015.

Conclusion

Even in its earliest stages, BHEF's STEM Education Modeling Project has yielded insights that are of potential use in the current federal and state policy conversations. As the Elementary and Secondary Education Act and America COMPETES undergo reauthorization and as states begin implementing their Race to the Top initiatives, BHEF and its partners are uniquely positioned to help decision makers consider a broad range of interconnected factors related to increasing the number of STEM graduates.

To this end, BHEF and its partners are **building awareness and demand** for the model in particular and use of this technique among policymakers and educators in general, and **refining and augmenting the existing model.** Within these two domains, BHEF is exploring opportunities to:

- Adapt the model for use by states, using Ohio as a pilot.
- Use modeling to examine the role of two-year colleges in meeting U.S. education attainment goals.
- Encourage policymakers and others to use these types of analytical tools to explore and advance education improvement and innovation efforts.
- Enhance the portion of the U.S. STEM model that pertains to teachers.
- Expand the model to encompass graduate education.
- Incorporate additional influences on mathematics proficiency and STEM interest at the P-12 level and on STEM persistence at the undergraduate level.

Together, these activities will enable BHEF to take a lead role in maintaining our nation's competitiveness by developing a robust STEM workforce.

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APPENDIX A:
SECURING AMERICA'S LEADERHIP IN SCIENCE, TECHNOLOGY, ENGINEERING, AND MATHEMATICS (STEM) INITIATIVE
Working Group

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