

America Disrupted: Dynamics of the Technical Capability Crisis

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in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

September 2008

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Submitted to the Systems Design and Management Program and the Engineering Systems Division
on August 8th, 2008 in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

ABSTRACT

This study investigates the cause of the nearly twenty-five year decline in the percentage of U.S. born undergraduates earning degrees in engineering. This dramatic decline has occurred despite incredibly high pay and low unemployment among individuals holding engineering degrees. On the surface, this situation appears to be violating the basic laws of labor-market supply and demand. A system dynamics model was created to represent the institutional forces and feedback loops present in the real-world system. This model internally represents the economic forces governing the choice to pursue science, technology, engineering, and mathematics (STEM) education, distinguishing features of highly quantitative knowledge that constrain its transmission, and factors determining the overall quality of STEM education in our schools.

This work presents a theory that high industry pay for STEM workers and low pay for STEM K-12 teachers directly cause long-term labor shortages that are self-perpetuating. A scarcity of STEM workers will cause wages to rise as employers bid up the price of those skills in the short-term. Schools are left with fewer qualified and lower quality teachers. This makes labor shortages worse ten to twenty years down the road. The fact that mathematics knowledge is highly sequential with strong dependencies on past-performance exacerbates the situation. Students who fall behind in mathematics find it nearly impossible to catch up. This work explores many societal shifts that occurred in the 1950's through 1980's that could have resulted in the perplexing behavior seen from 1985 until the present day. Finally, policy proposals to correct the situation are simulated in the model to test their ability to move the system in a more positive direction. The system is found to exhibit "tipping point" behavior. Small reforms will have negligible impact while larger reforms have the potential to make the system move into a fundamentally better pattern of behavior, but only after considerable delays.

In addition, this work presents a speculative hypothesis for the cause of Kondratieff economic long-waves briefly in an appendix based on unanticipated behaviors present in portions of the model.

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Acknowledgments

Words cannot express the thanks I owe to my wife Jessica for the loving support she gave when I went back to school, especially in the end days while I was completing this thesis. The work took on new significance when we learned of the baby she is now carrying.

I am very grateful to my advisor, J. Bradley Morrison, for his expert guidance on the art and science of system dynamics modeling. Most important was his insistence that computational modeling is useless unless it is grounded in real world problems and can be used to effectively communicate with a more general audience.

I must thank Paul Newton and Michael Richey of the Boeing Corporation for introducing me to the problem being studied here, providing valuable feedback, and helping to promote this work both internally and to a wider community of stakeholders.

Countless people have seen me present these ideas and have given feedback that moved work in new directions. Many others have helped edit this written report. All of them have made it much better than it would had I been working in a vacuum. I am grateful for all of their insights.

Throughout life, I have been extraordinarily lucky to have Betty and Dave, two loving and tough parents for whom education was always the highest priority. They sacrificed a great deal to give Paul, Lee, and I excellent opportunities.

As a result, I've been blessed with many wonderful teachers over time including Mrs. Horowitz in 2nd grade, Mr. Paul in 5th grade, and the entire faculty at the *Thomas Jefferson High School for Science and Technology* in Alexandria, Virginia. I wish every child could be as lucky as I was. I've also been fortunate enough to receive guidance at different points from mentors including John Paul Parker and Richard Matthews.

Finally, I want to thank all of the people responsible for sustaining the System Design and Management program and the Engineering Systems Division. *Mens et Manus*.

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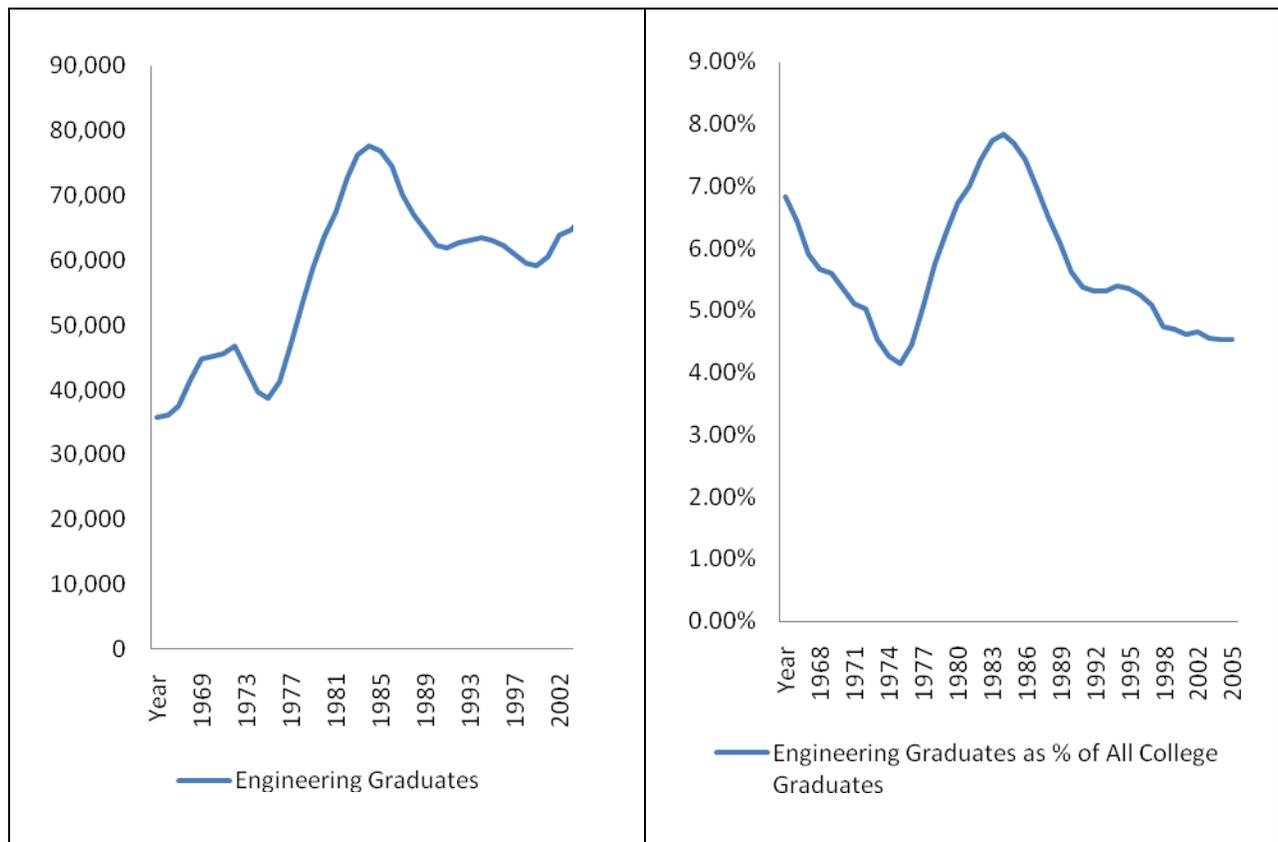
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1 Introduction

1.1 Thesis Statement and Primary Research Objectives

The percentage of students earning Bachelor's degrees in engineering is almost half what it was in 1985. This decline has occurred despite the fact that wages for engineering graduates are higher than those of any other degree-type. Unemployment for scientists and engineers has just hit a record low. What is being studied in this thesis is an apparent contradiction: people decreasingly willing to go into a field in which wages are extremely strong. On its surface, this situation appears to fly in the face of the law of supply & demand.



Throughout this thesis I will develop a model-based theory that explores this paradox. The theory proposes that extremely strong wages for science, technology, engineering, and mathematics (STEM) workers combined with low science and mathematics teacher wages in K-12 education directly cause long-term labor shortages in technically oriented fields that get worse over time because of positive feedback loops in the system. The architectural relationships between the U.S. systems of government,

K-12 education, academia, and industry are set up to systematically under-develop the quantitative and analytical skills that the economy desires most. Multiple societal shifts in the 1950's, 1960's, and 1970's (many of them positive) triggered unintended behaviors present in the system today.

I will then show that some policy reforms are capable of improving the situation, while others may be entirely useless. Most effective reforms will require sustained investment over long periods of time before their benefits are fully realized. Even after implementing effective reforms, the situation may actually appear to get worse in the short term because of the immense momentum built into the system. Furthermore, incremental or piecemeal fixes may have no impact because the system exhibits “tipping point” behavior. Under the current configuration it is stuck in a poor operating region. There exist other more beneficial operating regions that could be moved into if reform is powerful enough to “tip” the system into those other regions of behavior.

The research method uses the model in three ways:

- ***Reproduce history***: Iteratively construct system dynamics models that can endogenously reproduce the simultaneous long term strength of engineering wages and long term decline in U.S. born engineering graduates. Justify all structural relationships in the model with relevant supporting literature so that the results of the model are believable.
- ***Project history into the future***: Once models are capable of plausibly reproducing history, use them to understand what the future might hold for the strength of the U.S. technical workforce if current policy is maintained.
- ***Test alternative futures***: Test various policy proposals aimed at increasing the number of U.S. born engineering graduates to see if they are capable of increasing future graduation rates significantly above those produced in the forward-looking historical run. Attempt to determine if they will be effective if applied in the real world.

1.2 Problem Importance

The subjects explored here have profound implications for the continued prosperity of the United States. It is generally acknowledged that technological advance is the main driver of America's GDP. The health of U.S. based high-tech firms should be important to anyone worried about employment levels in the broader economy. According to the recent report jointly published by the National Academy of Sciences, National Academy of Engineering, and Institute of Medicine titled *Rising Above the Gathering Storm* (NAE, 2007 p. 29), “scientists and engineers tend, through innovation, to create new jobs not only for themselves but also for workers throughout the economy.” Unlike professionals in other high-paying careers such as finance or law, engineers and scientists not only create value for themselves and their firms, they also tend to generate growth for others as a result of their economic activity. This is because the primary focus and daily activity of an engineer is the creation, rather than the capture, of economic value. Promoting a technical economic base is therefore fundamental to securing our presently-high standard of living.

Shortages in the supply of technically-capable people in the labor pool could force U.S. firms to outsource jobs for two reasons. Most obviously, if not enough employees exist to meet business demands, then

outsourcing must take place. Secondly, shortages in the labor force will drive up the price of high-tech skills beyond their already high price. As globalization reduces the costs associated with managing global operations, the widening gap between what firms must expend to employ local vs. foreign labor will increase the frequency of outsourcing. Under one nightmare scenario, these two effects could merge to form a picture similar to Clayton Christensen's concept of "disruption." (Christensen, 1997) Under such a scenario, American wages could remain strong at the same time that many highly skilled jobs move to developing countries. The most stable remaining jobs would be those that are "sticky" or hard to move abroad. Many of these jobs are in the defense sector. Such jobs are less likely to produce exportable products that help improve the balance of trade. In addition, sticky jobs may be relatively less likely to lead to the types of innovation that drive economic growth or create new jobs. Ultimately under this scenario, the American high-tech industry could be transformed from a global powerhouse into a cottage-industry, taking the U.S. economy with it.

Maintaining a healthy number of individuals in the STEM educational pipeline that produces technically oriented workers is important to the future health of the country. Keeping American technical workers satisfied with their jobs is important, but rapid wage growth in the short term could lead to elimination of those jobs in the medium to long term as America is disrupted.

1.3 Thesis Organization

This work will be organized into three main parts. In the first part a conceptual model will be incrementally presented and supported by multi-disciplinary literature and data. This model will be built with the goal of accurately representing the structure of the system and some of the main causal drivers that influence the number of U.S. born engineering graduates. The main components of the notional model presented will be:

- Supply and demand feedback loops showing how the career opportunities available to STEM workers affect the decision of currently enrolled students to maintain interest in STEM education and ultimately pursue a STEM career themselves.
- A STEM education pipeline representing the number of students who continue to incrementally build mathematics competence at different stages of education.
- A teacher quality loop that shows how the career opportunities available to STEM teachers influence the quantity and quality of the teachers that educate students in the pipeline.

Simulations will then be presented to highlight the behaviors of this system. Graphs will be shown that demonstrate a qualitative similarity between what has actually happened, and the behavior produced by the model. The simulation graphs will also project thirty years into the future (until 2040) to indicate where the system is likely to move if current policies are maintained.

Finally, simulation results will show the effectiveness of a variety of policy fixes. The historical model will be used as a starting point. Historical behavior will continue until 2008 when changes will be introduced. Differences shown between the "historical" run and the "policy" run between the years 2008 and 2040 will highlight either the usefulness or inefficacy of different proposals under consideration by policy makers today.

Throughout this work, conceptual models will be presented that convey the meaning of the full simulating version of the model. Equation listings and block diagrams for the full version of the model are presented in appendices.

1.4 Project Context

This project began as a collaborative effort with the Boeing Corporation. This relationship was initiated by Dr. Brad Morrison at Brandeis University. Boeing (and other companies) engaged students in Dr. Morrison's '*Applications of System Dynamics*' course as external consultants to apply system dynamics modeling expertise to aid in the understanding of their business problems. Boeing wanted to use system dynamics modeling to bring a fresh perspective to some of the problems articulated in two well respected reports published by collaborative groups spanning academia, industry, and government:

Rising Above the Gathering Storm:

Energizing and Employing America for a Brighter Economic Future

Committee on Prospering in the Global Economy of the 21st Century

An Agenda for American Science and Technology

National Academy of Sciences, National Academy of Engineering, Institute of Medicine
2007

(NAE, 2007)

A Test of Leadership

Charting the Future of U.S. Higher Education

A Report of the Commission Appointed by

Secretary of Education Margaret Spellings

September 2006

(U.S. Department of Education, 2006)

Both reports are publicly available and can be found online. These reports discuss the importance of STEM to our economy and threats to American competitiveness. They compile a great deal of publicly available data and offer opinions on policy solutions intended to address such problems. Although my opinions and findings of this thesis do not always agree with interpretations of data and policy recommendations found in these reports, both are good places to start when trying to understand the challenges America faces and the current state of thinking about the causes and solutions to those problems.

Paul Newton (Boeing Phantom Works) provided modeling guidance and both Paul and Michael Richey (Boeing Learning Training & Development) provided context for the effort by serving as 'clients' to ensure that modeling focus continued to meet Boeing's needs. Paul and Mike gave support, but offered little direct guidance, preferring to see what emerged.

Boeing's stated concern revolved around the future of their technical workforce. A large portion of Boeing's engineers will be eligible to retire in the next ten years. Boeing fears that the U.S. is not producing enough engineers to replace these domestic retirements and meet future growth demands.

They therefore wanted modeling to focus on the causal relationships that affect the number of engineers in the U.S. with the goal of finding high-leverage policies to improve the current situation. They believe that this problem is extremely salient to most U.S. based engineering and information technology firms. They also believe that this is a “tragedy of the commons” (Hardin, 1968) that cannot be addressed by companies individually.

Since the completion of the class based project in the spring of 2008, Boeing and I have discussed the formation of a collaborative to use modeling to understand all issues surrounding the health of the U.S. science and technology enterprise. The goal of this effort would be to bring together stakeholders from industry, academia, K-12 education, and government to jointly explore problems of national importance in a “model-centric” way. A principle held by those participating in such an initiative would be that allowing stakeholders to communicate and debate their beliefs through the exploration of simulating social-science models, rather than simply rhetoric, would facilitate communication and alignment. An initial collaborative effort includes Boeing and Sandia National Laboratories. I have presented this work to multiple audiences and will continue to refine the content in preparation for a coordinated presentation later this year to promote the larger effort.

1.5 Methodology

1.5.1 System Dynamics Modeling

System dynamics models apply control theory to aid in the understanding of social systems. Building a model is usually done by first creating a diagram of causal relationships and feedback loops and then translating the conceptual model into a set of time-based ordinary differential equations that can be simulated to capture the model’s dynamic behavior. Going through the process of modeling allows one to explore and gain insight into the functioning of a real-world system's behavior by performing tests that are infeasible in the real world. This process is useful when trying to explore the long-term behavior caused by complicated relationships across institutional boundaries. System dynamics models differ from more commonly used types of models (such as spreadsheets models) because they adequately capture time delays, represent feedback loops, and do not rely on assumptions of linearity.

(Appendices in this report contain block diagrams and equation listings for the model presented here.)

An important aspect of an inductive (theory creating) modeling process (Christensen, 2006) (George, et al., 2005) (Van Evera, 1997) is that it allows (and enforces) consistency of thought. Modeling can be a good way of confronting ideological and “sound bite” based arguments. Forcing people to express opinions about the relationships governing the 'physics' of a social system through a collective modeling effort can allow multiple opinions and perspectives to be tested alongside one another in a way that would be impossible through real social experimentation.

Models embody theories about how the world is structured. Simulating the dynamic behavior of models over time forces the theorist to improve the model until it can generate results that are useful, plausible, and maintain internal consistency. This can lead to new insights about the way the real world behaves. While all models are oversimplifications, the goal is to create a caricature of the world that is useful in solving or developing ideas to solve pertinent problems.

Readers who wish to better understand the field of system dynamics and how system dynamics models are created and used are encouraged to read *Business Dynamics: Systems Thinking and Modeling for a Complex World* by John D. Sterman (Sterman, 2000), and *Principles of Systems* by Jay W. Forrester. (Forrester, 1971) The main journal covering the field is the “System Dynamics Review.”

1.5.2 System Dynamics in this Project

System dynamics modeling was chosen for studying this problem because its strengths include situations when:

- The structure of the system is fairly well understood, but its complex behavior is not.
- ‘Macro’ level aggregations are acceptable as representations of the system.
- Dynamic behavior emerges over large time-horizons.
- Relationships contain feedback and non-linearity.

All of these criteria were met. Individual relationships between government, industry, academia, and K-12 education can be described fairly easily. What is not understood is how those institutions evolve over time as a result of their interactions with each other. Given the problem statement, it is appropriate to model student behavior and the functioning of the economy in the aggregate. The emergent behavior this model will try to shed light on unfolds over years and decades rather than weeks and quarters. Finally, the institutions that make up the system under study all influence each other simultaneously.

This project involved iteratively reviewing literature and collecting subject matter expert opinion over time. The model was developed through several stages of refinement. At every stage, insights about the system derived from model simulation were used to plan further development and experimentation. The ultimate goal was to come to a better understanding of the causal mechanisms behind what appears to be a market failure. The final model presented here is a culmination of these efforts.

This model is *incomplete*, as any model representing a complex system will always be. This should not be confused with *invalid*. Although still a research tool, it has reached a stage that gives confidence that the insights gained by using it should be considered and further tested. One drawback to the model is that it does not adequately endogenize macroeconomic behavior of the U.S. economy. Integrating this model into a model of the national economy might make it possible to tune parameters to more accurately reproduce historical behavior in a *quantitative* sense. If that is done, it is possible to have some confidence in point predictions made for future system states. Even at this stage however, it is possible to observe behavior in the model that is *qualitatively* similar to the phenomena under study. The true goal of a model is not to perfectly reproduce historical behavior. No model can truly be verified or validated. (Sterman, 2000 p. 846) Rather, the goal of a model is to give insight that allows one to better understand the system and make more effective choices when devising policies that are capable of affecting positive change.

1.6 Common Explanations

The first task undertaken in this effort was to gather common opinion about why the problem is occurring. I asked more than 50 ordinary people their opinion on why students would not study a subject that was so lucrative, and why such a dramatic decline would occur between 1985 and 2008. It was hoped that my informal sample of public opinion might generate some useful hypotheses that could be explored in a model. Opinions that were commonly given include the following:

- Children today are lazier than they used to be, they used to have better work ethic. This is the “me generation.”
- Parents are more permissive than they used to be, they either don’t drive children hard enough because they “want them to be happy,” or they don’t pay enough attention at all.
- People raised in poverty will go into (or push their children into) professions that promise comfort but people raised in comfort will feel no such urgency. Because kids today have everything they need and want, they aren’t motivated to study hard subjects with the hope of future return.
- People today fear the prospect of putting time and effort into studying science and technology, only to see all of the jobs in those fields outsourced to developing countries.
- STEM workers are not perceived as nationally important like they were during the Cold War. (*Sputnik effect.*)
- It has something to do with increased participation of women in higher education and their relative tendency not to pursue engineering degrees.
- STEM workers are not respected like doctors or lawyers.
- STEM workers are not ‘cool’ like rock stars and basketball players.
- STEM subjects are harder to grasp and require more homework and time spent out of class.
- STEM subjects are not as interesting as non-STEM subjects.
- STEM subjects are for nerds. The opposite sex will not find you appealing.
- There isn’t as much need for engineers and scientists because computers and automation continue to make the design process so much easier.
- You can make more money in other fields such as business, law, medicine, etc.

Some of these opinions are more valid than others. Many of these common opinions will be disputed throughout the course of this research paper. One that already has been rejected is the idea that a person can make more money by studying other subjects. Even if this opinion is unjustified however, it still could have a causal impact on the number of students leaving STEM if it is widely held. Although some of these opinions may be valid, it is important to question whether any could really cause the behavior present in the system, and whether they have really changed very much since 1985.

1.7 A Note on Blame

One thing that must be stated clearly is that there is no individual or group that can be directly blamed for the problems presented in this research. The architecture of this system is defined by the structural relationships between stakeholders in K-12 education, academia, industry, local government, and federal government, as well as the implicit policies embedded in those relationships. The complex behavior of this multi-stakeholder system brings about the results presented here. Everyone in the system can be behaving rationally and with good intentions and still produce these dynamics. When discussing this problem, it is common to hear assignments of blame to various parties including government officials, corporations, teachers, unions, foreign competition, and (most disturbingly and commonly) even to children. Blaming individuals or groups in this way is not an effective way to understand what is actually happening so that the system may be reformed. The intent of this work is not to find one individual or group that can be directly blamed for the problems but rather to better understand how the structure of this complex system relates to the undesirable patterns we observe.

2 Building a Conceptual Model

2.1 Exploring Supply and Demand for STEM Talent

2.1.1 Current Engineering Wages

America's continued economic strength relies on its ability to lead the world in scientific and technological advance. This, in-turn, depends upon a healthy base of indigenously educated technologists. Opportunities for American engineers and scientists abound. A longitudinal study conducted by the National Center for Education Statistics found that people who got Bachelor's degrees in STEM subjects earn over ten-thousand dollars more per year than their non-STEM counterparts. Engineering and computer science degree holders fared the best, earning a substantial premium above all other college graduates. (NCES, 2008). This study contained the following table demonstrating the point:

Salaries of full-time employees by degree type and number of years since degree earned			
	1-2 years (1994)	4-5 years (1997)	9-10 years (2003)
Total	\$30,800	\$39,900	\$60,600
Engineering	38,900	51,400	74,900
Computer science	33,400	50,400	72,600
Business and management	33,800	43,400	65,900
Health	40,500	45,600	65,000
Biological sciences	29,200	33,900	62,200
Mathematics/physical sciences	27,100	37,800	58,200
Social and behavioral science	26,900	39,200	62,300
Arts and humanities	25,000	33,600	52,800
Education	26,600	31,700	43,800
All STEM fields	33,800	45,600	68,300
Non-STEM fields	30,200	38,800	58,900

Table 1: Longitudinal Salary Data by Degree Type

In addition to significant financial reward, high-skilled technical work offers career potential, opportunities for creativity, and other life-style amenities that are attractive to many. The same study found that during all three periods, engineers and computer scientists held the highest levels of belief that their current job had "career potential." STEM degree earners held these beliefs more strongly than those without STEM degrees. These careers provide remarkably stability as well. The NSF reported that unemployment among scientists and engineers reached a low in 2006 of 2.5%. (Kannankutty, 2008)

2.1.2 Historical Engineering Wages

Engineering wages have risen relative to other wages in the economy in the past 100 years as the value of information and knowledge increased. It is now estimated that the value of the information embedded in products as a proportion of cost of production is now higher than it has ever been. (Landes, et al., 2003) The following chart copied from (Herrnstein, et al., 1996 p. 93) shows that relative wages of engineers and manufacturing employees diverged widely over the course of the 1950's:

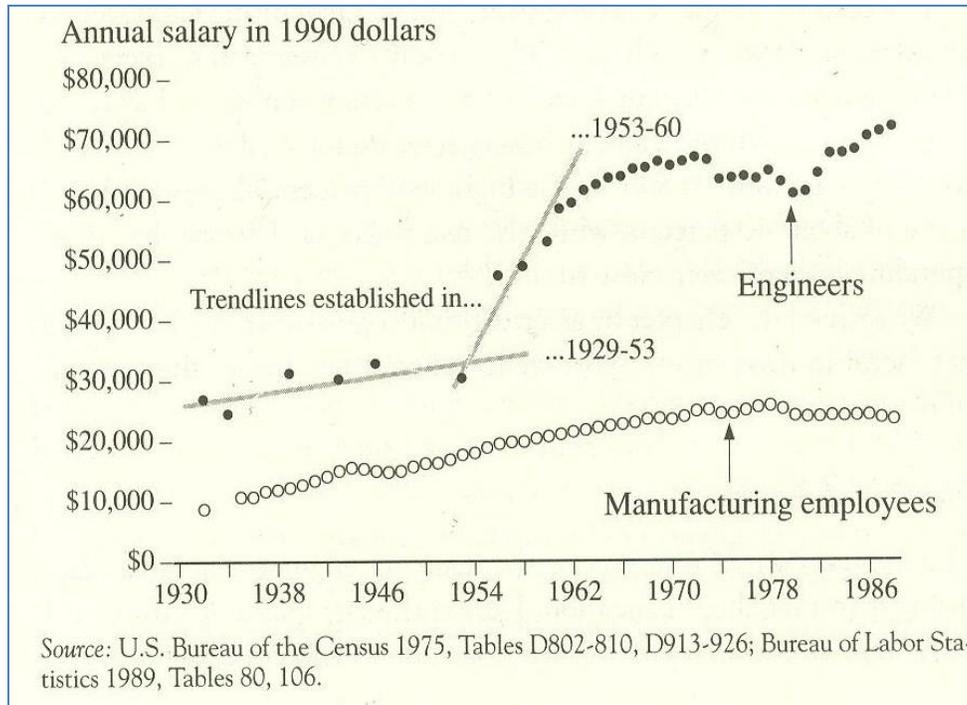


Figure 1: Historical Wages for Engineering and Manufacturing Jobs

The difference between median engineering wages and the U.S. median wage is substantial. Although engineering wages are not rising dramatically relative to median wages as they did during the 1950's and 1960's, engineers continue to do well financially. Since 1970 engineers have earned between 3 times and 4 times American median wages. It should be noted that this data only includes averages for the profession, not the type of degree earned. It therefore does not account for people earning Bachelor's degrees in engineering who then go into management, law, or finance for instance. Recently there has also been a tendency for Wall Street to compete with engineering firms over graduates with strong quantitative skills. Many engineering graduates today are going directly into finance and banking. The willingness of financial firms to 'poach' engineers and retrain them may be indicative of an overall shortage of quantitative skills among the college graduates relative to demand.

Data used to generate the following charts were extracted from various sources:

- U.S. median salaries were extracted from (U.S. Census Bureau, 2006)
- Median salaries for engineers were extracted from (Scientific Manpower Commission, 1967 - current)

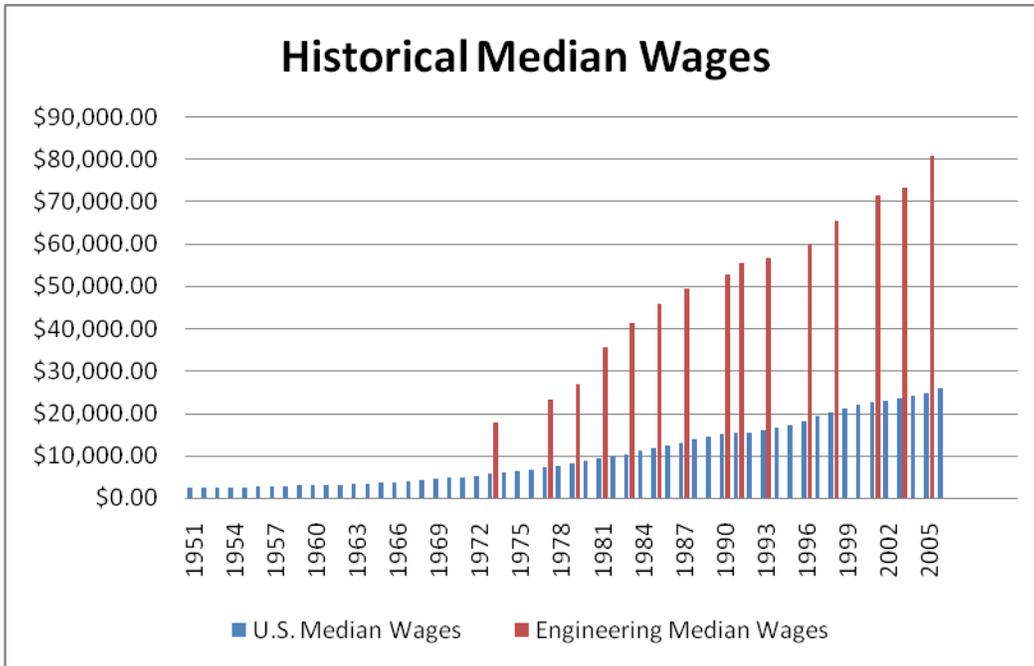


Figure 2: Historical Median Engineering and Average U.S. Wages

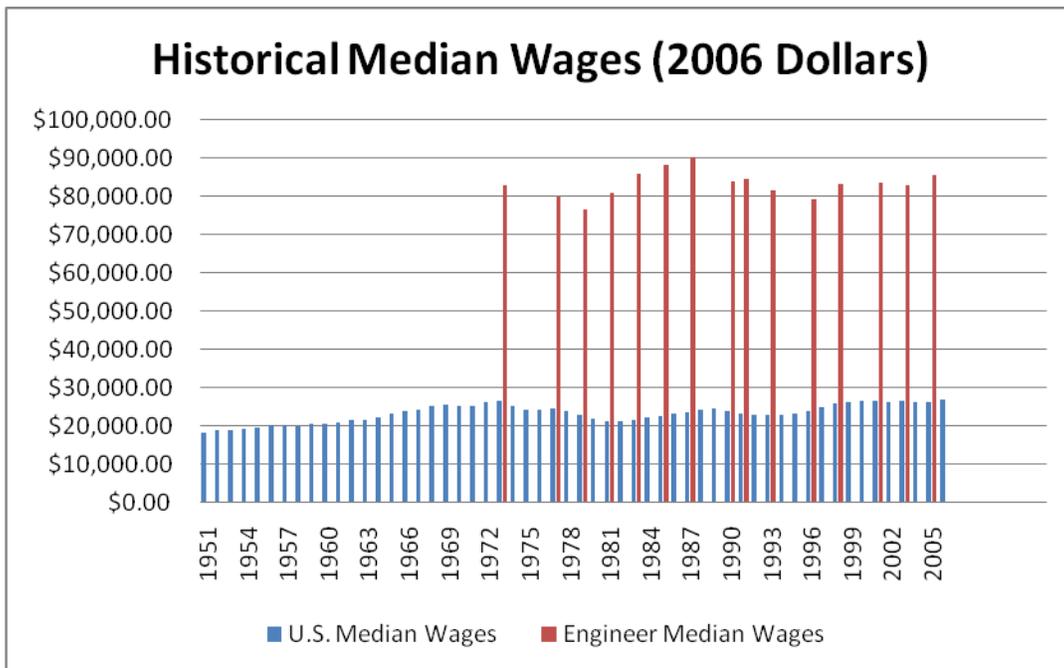


Figure 3: Historical Median Engineering and Average U.S. Wages in 2006 Dollars

2.1.3 Engineering Graduations

Despite the attractiveness of science and technology careers, there is evidence that American dominance in science and engineering may be threatened by a shortage of highly skilled technical labor. Many industrial and information technology companies are concerned that they will not be able to hire enough scientists and engineers to replace domestic retirements and to meet business growth demands. The impending exodus of 'Baby Boomer' technologists may exacerbate the current shortfalls and may cause STEM wages to continue to climb further. Surprisingly however, younger generations are increasingly unwilling to study STEM. Despite the pronounced pay disparity, the number and percentage of Americans graduating with engineering degrees has been trending downwards since 1985. The percentage of Bachelor's engineering degrees dropped from 8% to 4.5% over the course of that time. (NAE, 2007) The disparity between impending retirements and indigenous replacements has been described by the National Academies as a “Gathering Storm” (NAE, 2007) that may sap America's strength in those fields.

The following charts provide information about trends related to the percentage of people attending college and the popularity of different undergraduate majors over time.

Data used to generate the charts in the next few sections were extracted from various sources:

- All information about the number of students earning different undergraduate degree types on a yearly basis, either in total or by gender, can be found online in the NSF WebCASPAR system. See bibliography entry for (National Science Foundation WebCASPAR System).
- All information about the number of 22 year olds in the U.S. population during a given year was extracted from the U.S. Census Bureau web site from various current and archival population estimates. See bibliography entry for (U.S. Census Bureau Population Estimates).

22 Year-old Populations

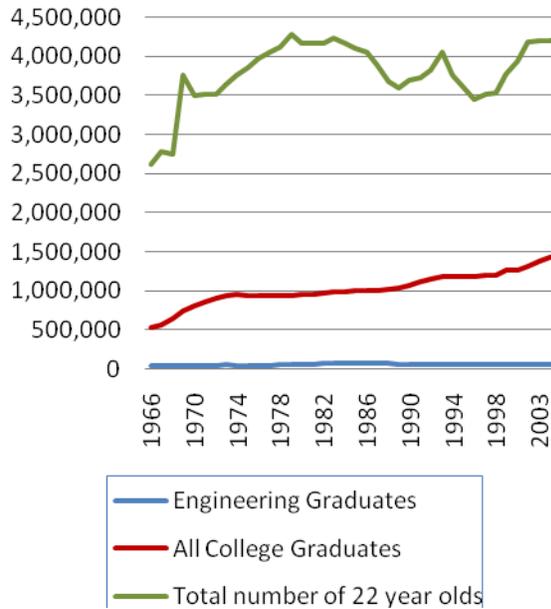


Figure 4: College Attendance

As the ‘baby-boomers’ came of age, the total 22 year old population swelled. A peak occurred around 1980. Since then, the population of 22 year olds has fluctuated between 3.5 million and 4.25 million.

The number of people earning college degrees has tripled from 500,000 to 1,500,000.

22 Year-old Percentages

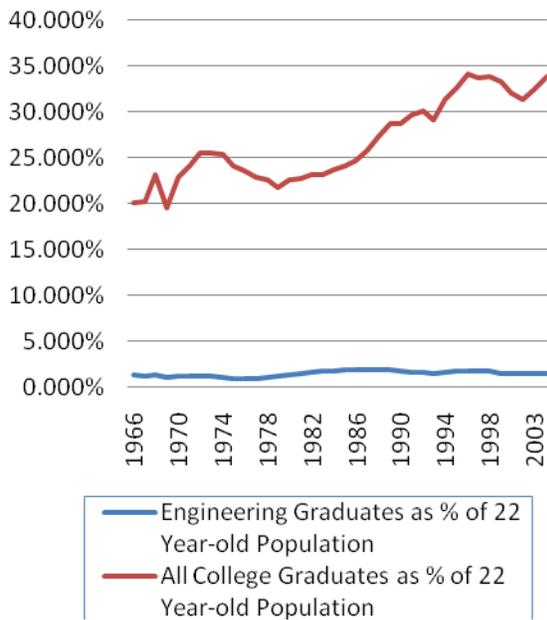


Figure 5: College Attendance Percentages

Over the course of this time period, the percentage of the population earning undergraduate degrees grew from 20% to 35% of the population.

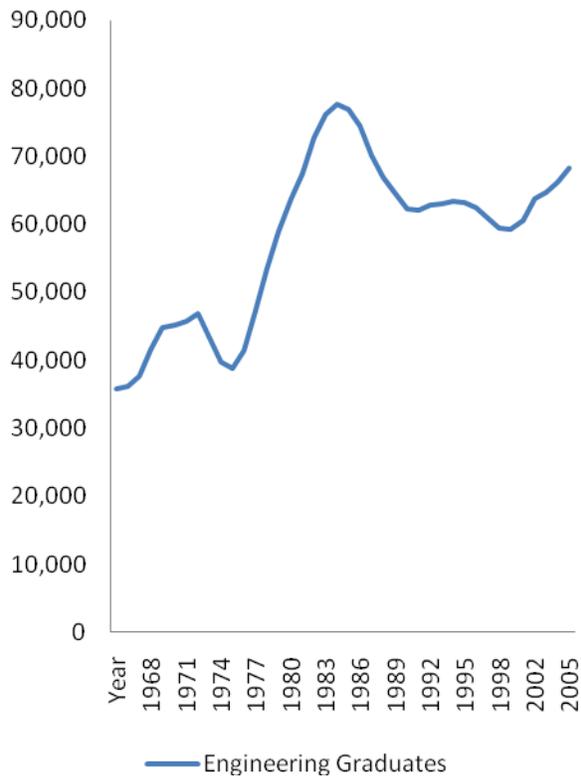


Figure 6: Engineering Graduation Numbers

This fast growth has not penetrated the engineering profession however.

The number of degrees awarded in engineering rose from 36,000 to 78,000 in 1985. It then dropped until it hit a minimum of 59,000 in 2001 and then started to rise again.

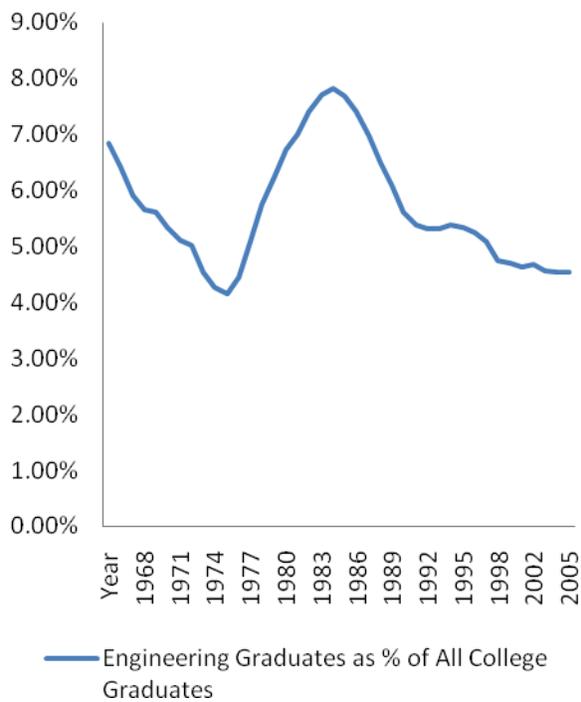


Figure 7: Engineering Graduation College Percentage

Unfortunately, this rise after 2001 does not reflect renewed interest, but rather a recent demographic influx. The percentage of undergraduates earning degrees in engineering fields peaked in the year 1985 at 7.83%. It has declined most years between 1985 and 2006, and is now at 4.54%. Although not depicted here, the percentage of students receiving degrees in computer science also experienced a peak in 1986.

It should be noted that the percentage of foreign-born students in American universities rose over this time period, and that foreign-born students disproportionately study STEM. This fact potentially masks numbers that would look even worse for American born students.

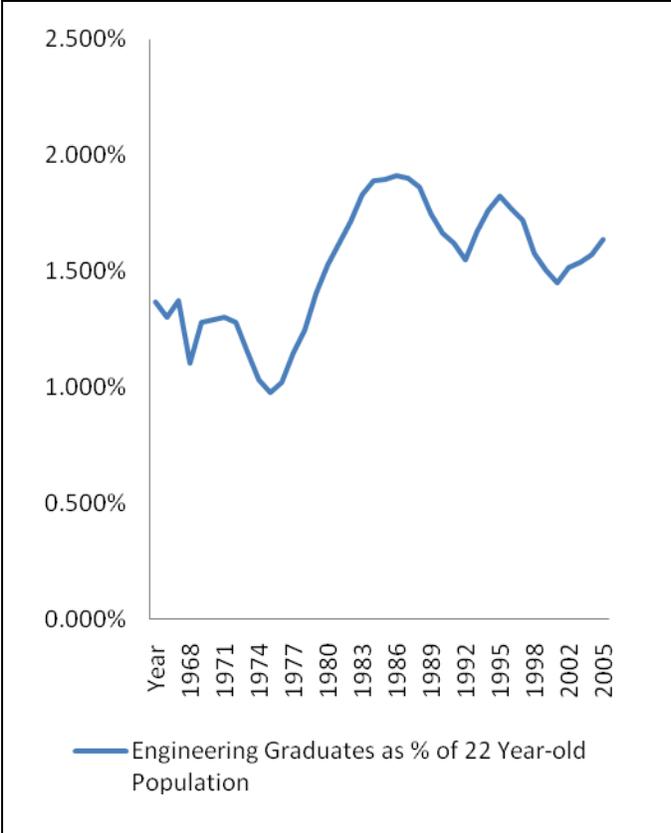


Figure 8: Engineering Graduation Percentage

The percentage of all people college age people earning engineering degrees has been trending downward since the mid 1980's as well.

2.1.4 International Comparison

The following chart showing data provided by the National Science Board that can be found in (NAE, 2007 p. 100). It shows the weakness of the U.S. relative to other nations in the percentage all 24 year olds who hold college degrees in STEM subjects.

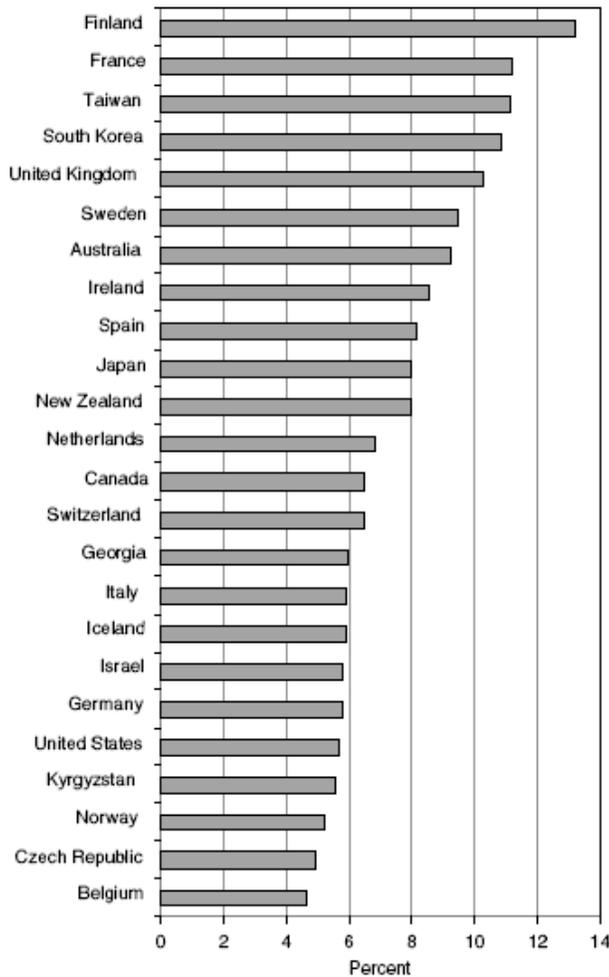
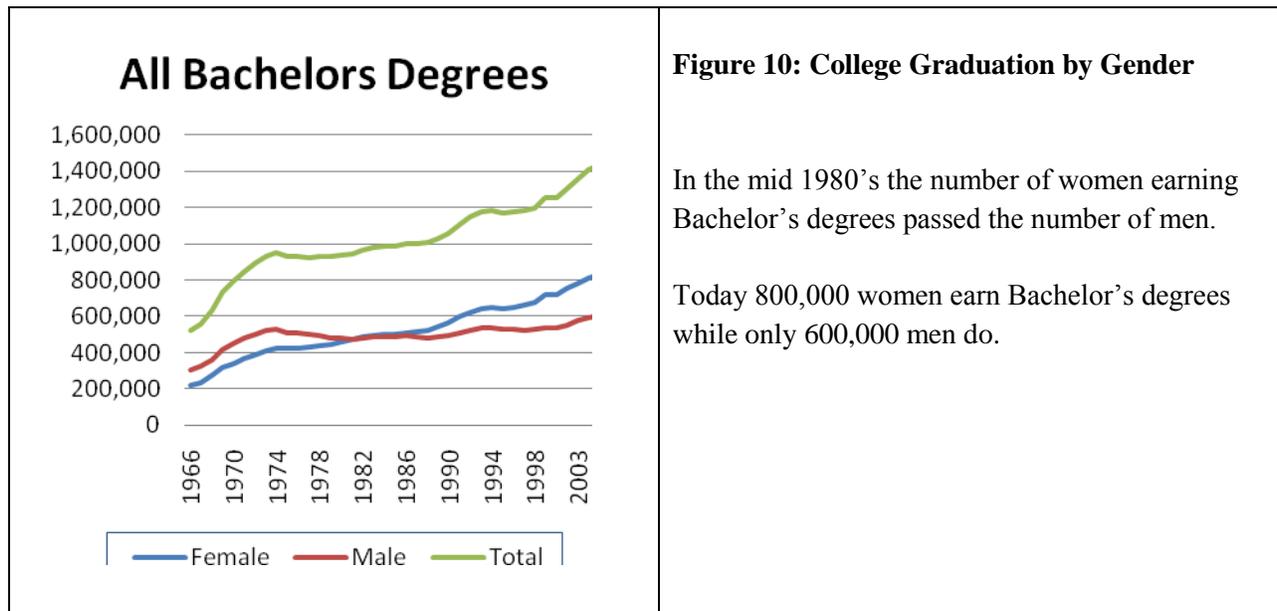


Figure 9: International Percentage of College Degrees in Engineering

U.S. higher educational institutions are considered the best in the world. Rapid declines in STEM interest among U.S. born students and weakness compared to international STEM graduation have created a good deal of unused capacity in engineering and science programs at the graduate level. This has necessitated the importation of foreign students to populate graduate programs. Fully fifty five percent of engineering doctoral students in the U.S. are now foreign born. (NAE, 2007 p. 35)

2.1.5 Gender Issues

The fraction of women in engineering is lower than in most other professions. It is reasonable to wonder what impact the increasing percentage of women in college has had on the overall percentage of university graduates earning engineering degrees. It is plausible to suspect that increasing female university enrollment combined with their relative tendency not to study engineering could be responsible for a decreasing percentage of graduates earning engineering degrees. This issue will be explored in the graphs below:



Engineering Bachelors Degrees

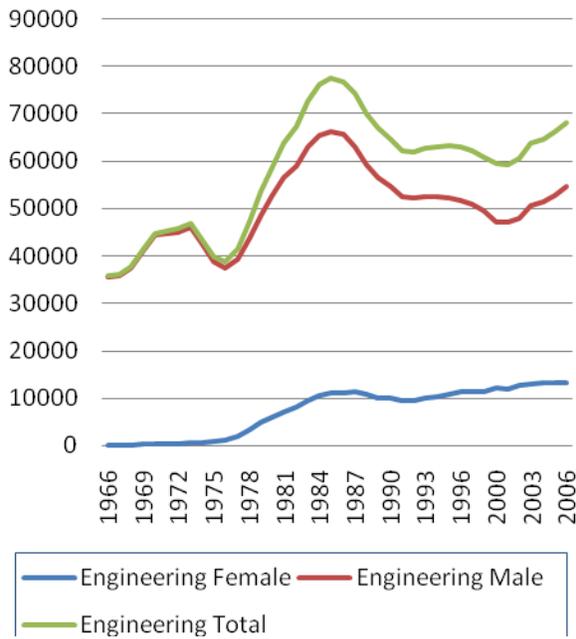


Figure 11: Engineering Graduation by Gender

The number of women earning degrees in engineering was negligible until 1975. The period from 1975 to 1985 saw a significant influx of women into the field. Growth was arrested thereafter. This ten year period occurred because of larger social trends related to the liberalization of gender roles in the workforce.

The shape of the curve of total engineering Bachelor's degrees is caused more by wild fluctuations in the number of men than the influence of women, because of their respective sizes in the population.

Female Engineering Degrees

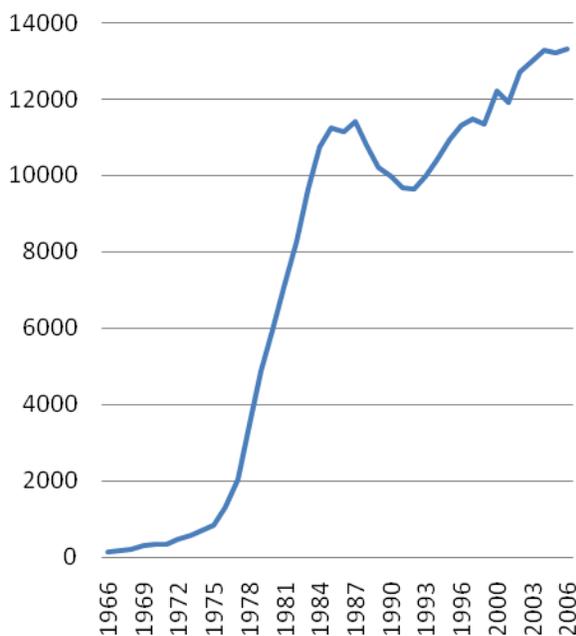


Figure 12: Female Engineering Degrees

This graph shows the number of women earning degrees in engineering on a larger scale. The number of women earning degrees also peaked in 1987, but went down thereafter and reached a local minimum in 1992. It began to recover earlier than the number of males in the field, surpassed the 1987 peak in 1997, and continued to rise thereafter.

Percentage of Degrees in Engineering

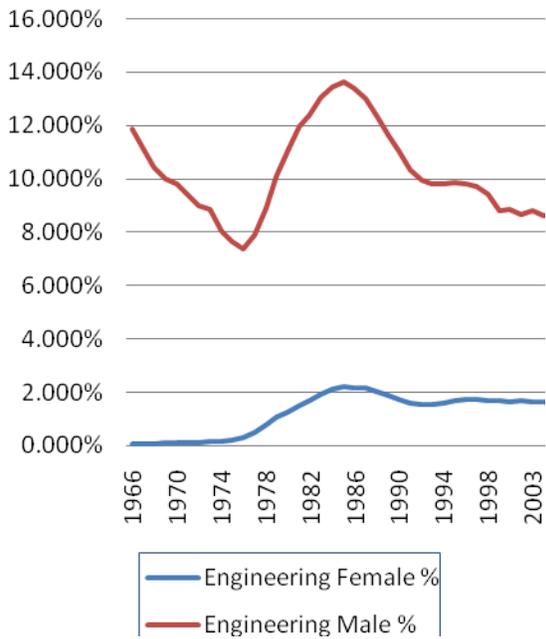


Figure 13: Engineering Percentage by Gender

The percentage of men in college studying engineering fluctuated wildly during this period. The percentage of women went from negligible to approximately 2% over this time.

Percentage of College Females Earning Engineering Degrees

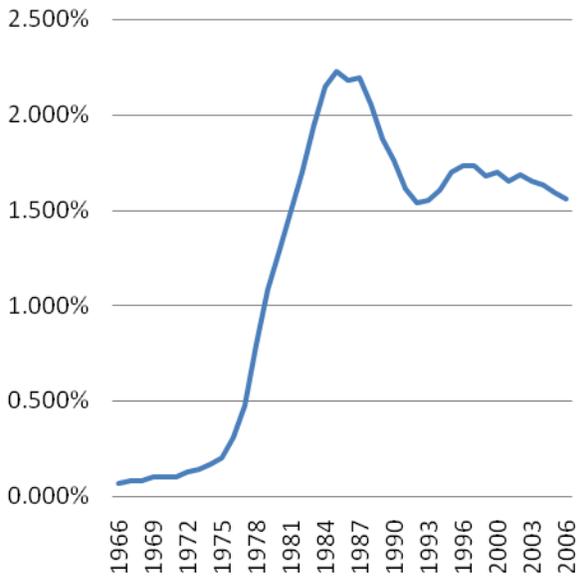


Figure 14: Female Engineering Percentage

This graph shows the percentage of women (relative to all college going women) earning degrees in engineering on a larger scale. Women after 1985 show the same general tendency of decline as men.

Ratio of Female to Male Engineering Preference

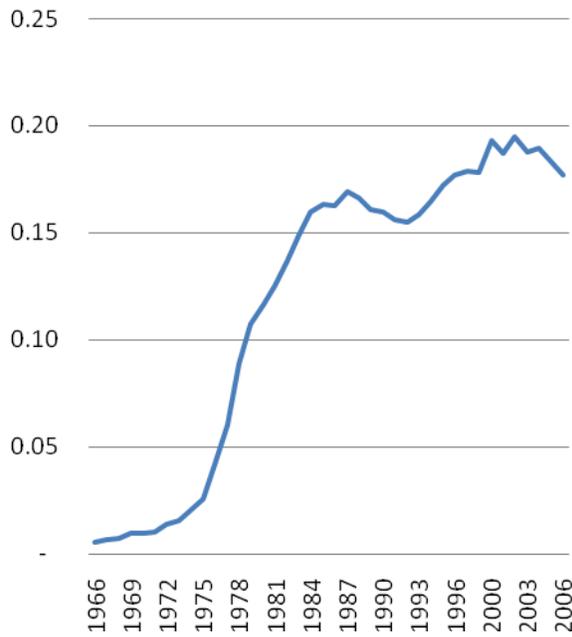


Figure 15: Ratio of Female To Male Engineering Preference

The ratio of percentage of women choosing engineering relative to the percentage of men choosing engineering indicates that engineering has become more popular with women than it has with men over time.

The previous graphs have demonstrated that although increased participation of women may be a solution to the problem of weaker interest in engineering, it is not a cause of the tendency toward decline that has been witnessed between 1985 and today.

In fact, although there is obviously a gender related influence causing there to be fewer females than males in engineering, one or more strong influences are causing movement in the percentages of people choosing engineering that operates independently of gender. These effects are visible in the data for both men and women at the same time.

2.2 First Conceptual Model: Invisible Hand Loops

Based on the above discussion, a first conceptual model will be presented that embodies supply and demand forces that produce engineers and impact the number of jobs available in the economy:

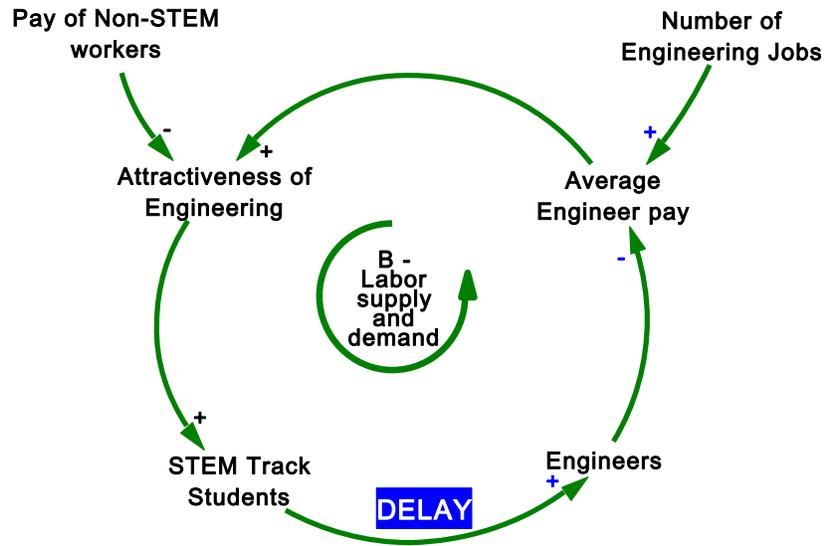


Figure 16: Labor Supply and Demand Conceptual Balancing Loop

The loop in this model represents an economic “Invisible Hand” regulating the number of people choosing to enter engineering. Arrows indicate causal relationships and polarities on those arrows indicate a positive or negative influence associated with that relationship. As the pay and benefits of the average engineer rise relative to the pay of workers in a non STEM fields, the attractiveness of engineering careers go up. If these jobs become more attractive, more students at every level will study the courses needed to allow them to enter a technically-oriented career either because they are attracted by those wages, or because their parents make them. After a delay associated with going through the educational process, these students emerge to cause an increase in the number of engineers. As more engineers enter the economy however, it will tend to depress wages if the demand for engineers remains the same. The wages of engineers in this model are determined by a simple supply vs. demand relationship. If the available jobs go up or the number of engineers goes down, then wages rise as employers bid up the price of those skills. Likewise, if the number of jobs goes down or the number of engineers goes up, wages go down (or at least increase at a slower rate) relative to the other jobs in the economy.

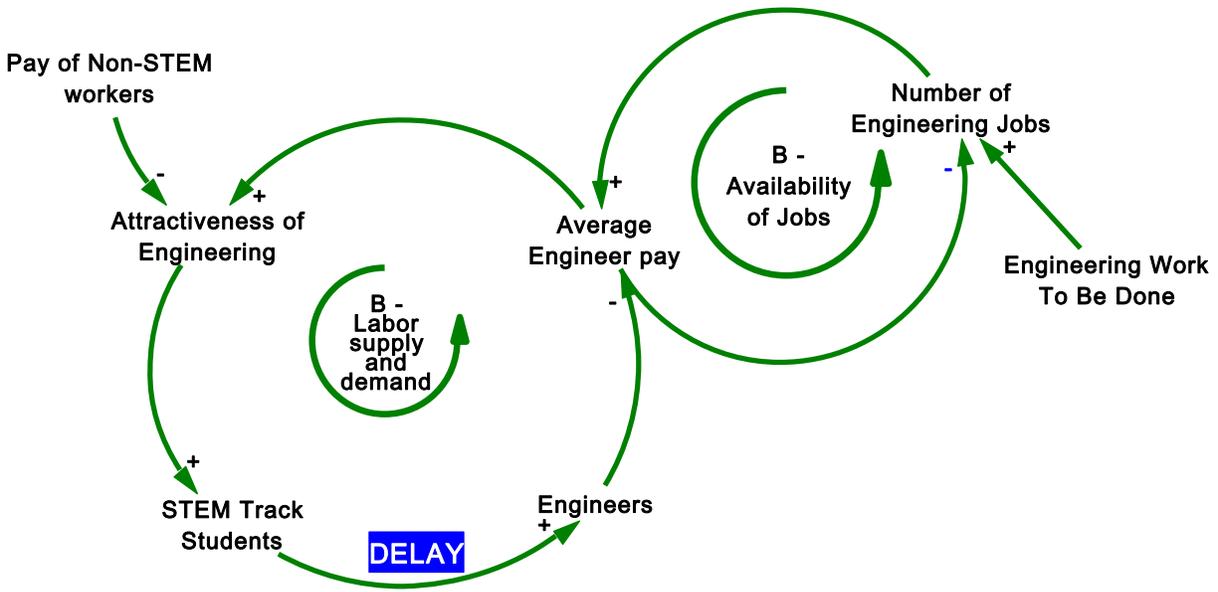


Figure 17: Availability of Engineering Jobs Conceptual Balancing Loop

A second conceptual loop has been added to the model to more accurately reflect the fact that as wages go up, employers provide a decreased number of jobs as they find substitutes, cut back on goals, or merely do without. Likewise, if wages in a profession decrease, employers will create more jobs because of the new profit potential associated with those decreased wages. In this simulation model supply and demand curve are implemented as non-linear lookup tables.

These two loops combine to complete a dynamic picture of the ‘Invisible Hand’ in action. This balancing feedback relationship brings stability to the system and generally causes the economy to respond to fluctuations in demand in a reasonable way. Many economists would tell you that the market for STEM labor should be functioning effectively because they only tend to consider the impact of these two important loops and the impacts of other structure such as collective bargaining agreements in the case of unions or cartel-like behavior on the part of physicians. Unlike these other examples, the market for engineering talent is relatively unhindered. Because the market for engineering talent does not appear to be functioning correctly however, we must continue exploring additional structure that could bring about pathological behavior.

2.3 Exploring the STEM Education Pipeline

The nature of the delay between increased student interest in STEM fields and the emergence of additional engineers must be more clearly understood.

Rising Above the Gathering Storm, it is articulated that:

Student interest in research careers is dampened by several factors. First, there are important prerequisites for science and engineering study. Students who choose not to or are unable to finish algebra 1 before 9th-grade—which is needed for them to proceed in high school to geometry, algebra 2, trigonometry, and pre-calculus—effectively shut themselves out of careers in the sciences. In contrast, the decision to pursue a career in law or business typically can wait until the junior or senior year of college, when students begin to commit to postgraduate entrance examinations.

Science and engineering education has a unique hierarchical nature that requires academic preparation for advanced study to begin in middle school. Only recently have US schools begun to *require* algebra in the 8th-grade curriculum.

(NAE, 2007 p. 102)

The fact that the ability to enter a profession requiring advanced mathematical training is dependent upon decisions made in the 8th grade or earlier has important implications. All educators interviewed over the course of this investigation agreed with its validity. Students who stopped studying mathematics at any point in their educational career almost never entered the engineering profession because the entry barriers were too high. Many argued that the decision points may be even earlier. Numerical concepts must be mastered before a student can effectively learn algebra. If they are not, a student may have fallen out of the “STEM Pipeline” prior to entering middle school.

The only point of discussion raised by some was to question whether this was an innate feature in mathematical knowledge, or whether it resulted from the way mathematics education and institutions of learning were structured. Most agreed that much of the effect had to do with the inherent nature of mathematics itself, and that a societal attempt to add “re-entry points” to the system might mitigate the problem somewhat.

In order to calibrate our model, studies were found which reported student interest in STEM and rates of progression or falloff at different levels. This gave a crude way to estimate parameters when creating initial models of the system. One extremely useful source of parameter information is the paper titled “An Analytical Control System Model of Undergraduate Engineering Education” by Grismore, Hurtig, and Farbrother. (Grismore, et al., 2003) This paper presents a control system model to estimate the

efficacy of school improvement at different grade levels to improve total STEM throughput. The following two tables are drawn from that paper.

This table shows students losing interest and dropping off fairly rapidly in the high-school and college years. Numbers presented are for the cohort graduating from college in 1984:

Student interest and pursuit of careers in natural sciences and engineering			
Stage	Year	Number of Students	
All high school sophomores (baseline)	1977	4,000,000	
High school sophomores reporting interest in natural sciences and engineering.	1977	730,000	
High school seniors reporting interest in natural sciences and engineering.	1979	590,000	
College freshmen with intention to study natural sciences and engineering.	1980	340,000	
B.S. Graduates in natural sciences and engineering	1984	208,000 (78,000 engineers)	

Table 2: Declining STEM Interest in Higher Grade Levels

This next table presents estimates provided by the National Center of Education Statistics (NCES) for the percentage of people who continue moving through the pipeline at varying stages. This study was published in 1998 and is also found in (Grismore, et al., 2003):

Retention Rates in the Engineering Pipeline	
<i>Note: MPC stands for Math-Physics-Chemistry</i>	
Fraction of middle school graduates prepared to take high school MPC courses	18%
Fraction of middle school graduates prepared to take high school MPC courses who actually enroll in those courses	75%
Fraction of high school students who actually complete the MPC courses (high school pathway retention)	81%
The fraction of high school students having taken all MPC courses who actually enroll in engineering	22%
Fraction of engineering enrollees who actually complete the educational program requirements. (engineering retention)	61%

Table 3: STEM Pipeline Drop-off at Different Grade Levels

One of the most devastating things to take note of is that 82% of students fall out of the pipeline sometime prior to leaving junior high school.

2.4 Second Conceptual Model: The STEM Gauntlet

Based on the above discussion, the conceptual model was modified to more fully articulate the structure of the STEM pipeline:

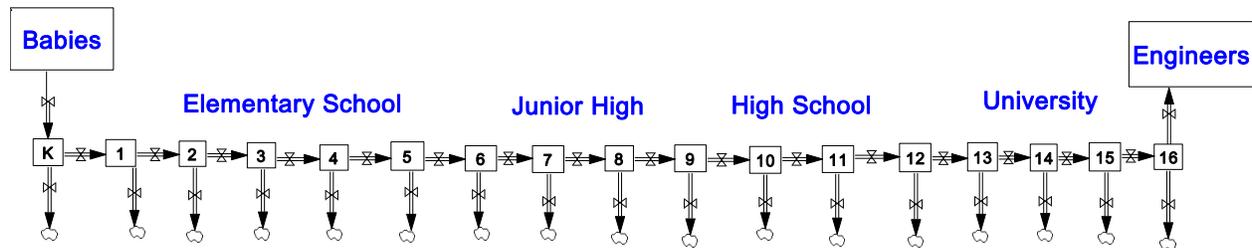


Figure 18: STEM Gauntlet Conceptual Structure

The above model represents a system dynamics “stock and flow” structure. People are stored in *stocks* represented by boxes and *flow* through different stages in the system. In this picture people start as babies and flow into kindergarten, flow through the rest of the educational pipeline, and then flow into the stock of engineers. Notice also that people can flow out of any stage into a “cloud”. These people have fallen out of the STEM pipeline most likely never to return. As discussed previously, the unique nature of mathematics education makes it extremely hard to return once this occurs. Therefore, this model assumes that if a person has fallen out of the system, they do not re-enter. This is fundamentally different from the nature of building knowledge in humanities fields that lack vertically structured chains of knowledge dependencies (NAE, 2007 p. 115), and therefore have lower barriers to entry.

The STEM pipeline structure is therefore been re-designated as the “STEM Gauntlet” in reference to the concept of “*running the gauntlet.*” This was a form of corporal punishment in which a soldier was forced to walk or run through a column of people that beat him at every step. If the individual made it through the gauntlet his life may have been spared and sins forgiven. If he did not, he may have been beaten to death. The slower a person moved, the more likely he was to die.

A student may be considered to have fallen off the pipeline even if they are still taking STEM subjects in school. This would be the case if they are taking courses that are not rigorous enough to enable them to eventually succeed in a university level science or engineering program. In order to better visualize the functioning of the pipeline, the following picture superimposes a crude picture of the subjects that must be learned at each stage with the number of students that complete and adequately learn those subjects within the timeframe necessary to continue to the next stage:

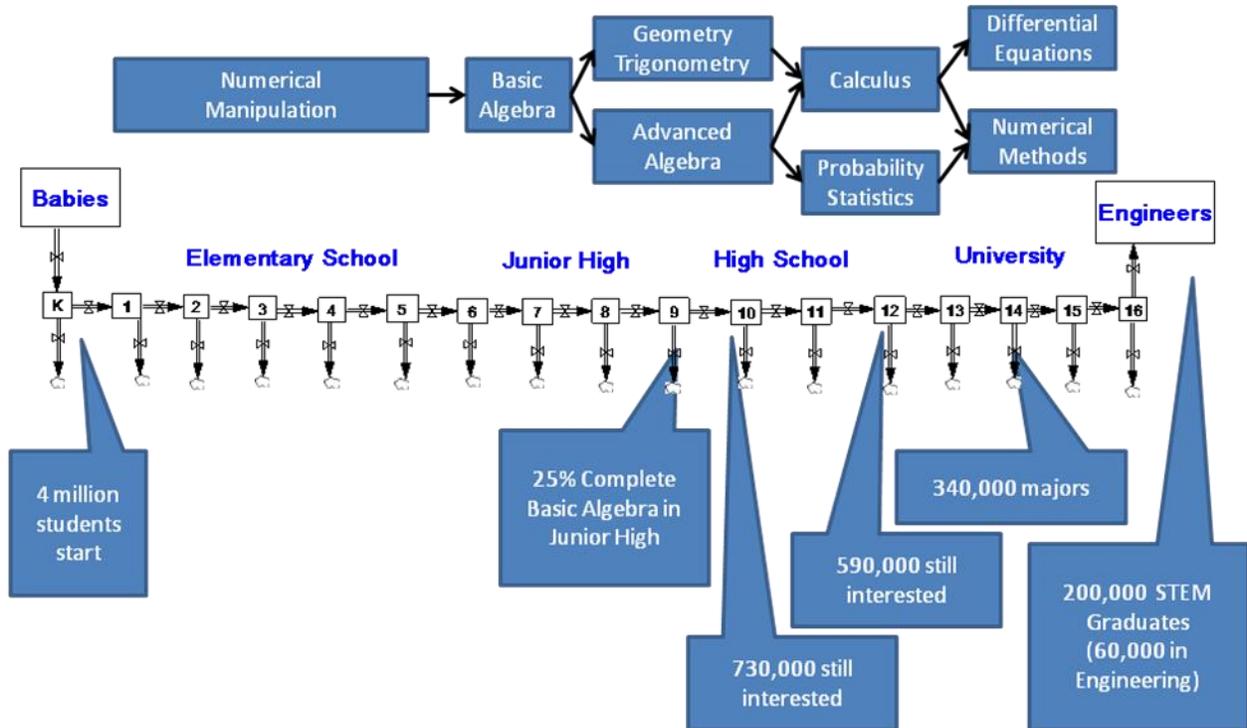


Figure 19: STEM Gauntlet Conceptual Structure with Subject Matter and Student Interest

The vertical nature of mathematics knowledge means that the production of engineers is subject to longer periods of delay than many other professions. The effect of a “signal” to increase “production” of engineers, caused by an increase in availability of jobs and rising wages, will not be fully felt until decades later because of this incredibly long pipeline in which reentry is not allowed. Although economic signals can convince STEM trained individuals to switch industries or gravitate towards other subjects, the stock of STEM capable individuals in the economy cannot be easily enlarged by transfers from other fields. Delays such as this limit the effectiveness of short-term economic signaling mechanisms because although they can cause a reallocation of existing STEM skills, they cannot increase the overall pool of STEM capable workers in the short term. This fact can be responsible for unresponsiveness in the short term and potentially lead to unstable or oscillating behavior in the long term.

2.5 Third Conceptual Model: Invisible Hand Loops with STEM Gauntlet

Now, the two models presented previously must be combined into a single structure. This combined model is depicted here:

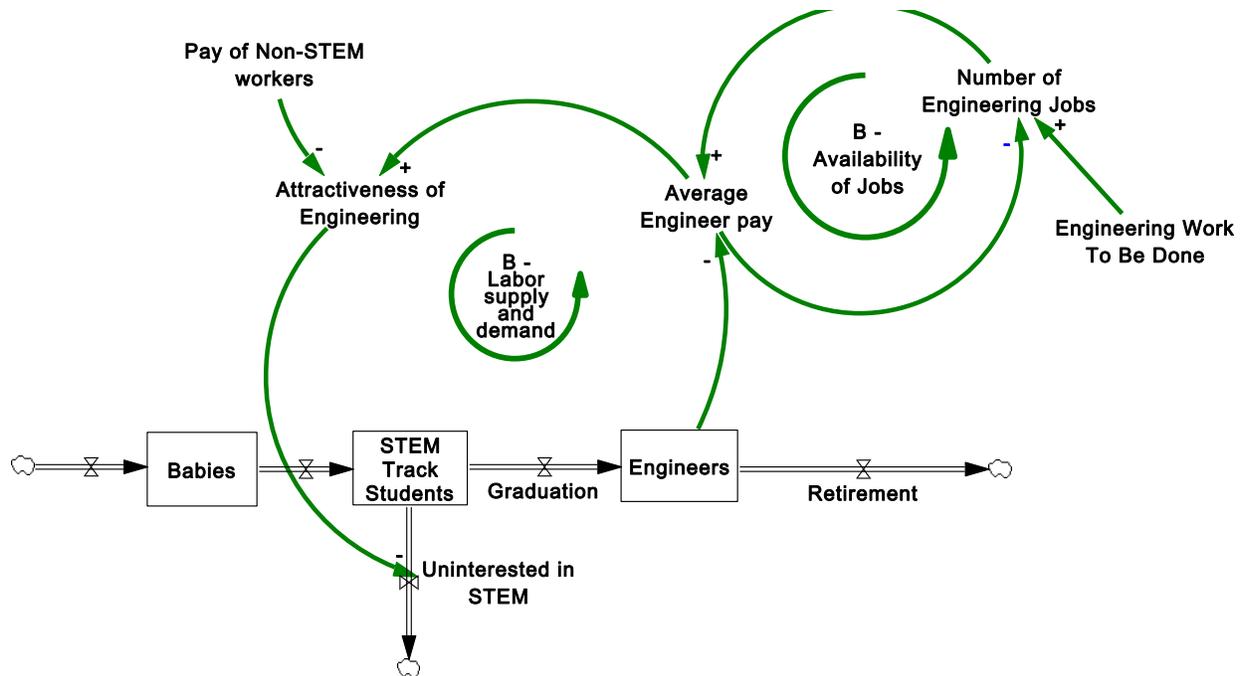


Figure 20: Supply and Demand Loops and STEM Gauntlet Combined

Now, instead of “Attractiveness of Engineering” directly causing an increase in the number of STEM track students, it instead is shown to reduce the outflow of potential STEM students (hence the negative polarity) into a cloud because they continue to stay interested in STEM. Decreasing this outflow has the effect of causing more people to go to the next stage, and ultimately more people emerge from the end into the pool of Engineers in later years. Although the STEM gauntlet is depicted here as a single stock of students, it is easy to imagine how the full gauntlet relates to the invisible hand structure in the simulation version of the model. The outflow in every grade is regulated by the “Attractiveness of Engineering.” The current amount of outflow into the pool of engineers will be the result not of the present level “Attractiveness of Engineering,” but of the level for “Attractiveness of Engineering” over the course of seventeen years. Over the course of this seventeen year period, “Attractiveness of Engineering” changed because wages and job levels moved. Its level was based in part on the number of engineers that had graduated from previous educational cohorts.

2.6 Exploring STEM Education

So far, student behavior has been examined only in terms of economic choices they (or those around them) make in response to the wage premium paid to engineers while they are in school. This has been the only determinant of the number of engineers or STEM workers that make it through the gauntlet. It is now important to examine other factors that may influence the retention rate of the STEM pipeline.

Student achievement in mathematics and science subjects should be related to gauntlet drop-off rates. This section examines American student performance in mathematics and science subjects relative to other countries to observe trends.

2.6.1 Student Performance

A commonly cited work that gauges subject matter performance internationally is the “Trends in International Mathematics and Science Study” (TIMSS) that is conducted by the International Association for the Evaluation of Educational Achievement (IEA). According to the National Center for Education Statistics, TIMSS “provides reliable and timely data on the mathematics and science achievement of U.S. students compared to that of students in other countries.” (NCES TIMSS Web site)

TIMSS has measured performance at the fourth, eighth, and twelfth grade levels in different years. Results have not been positive. Although U.S. fourth graders performed better than average and eighth graders performed close to the international average, twelfth graders scored well below the international average. The following table found in shows the average TIMSS scores of students from different countries (NAE, 2007 p. 132).

TIMMS 1995 Twelfth Grade Average Scores			
Mathematics		Physics	
France	557	Norway	581
Russian Federation	542	Sweden	573
Switzerland	533	Russian Federation	545
Australia	525	Germany	522
Cyprus	518	Australia	518
Lithuania	516	International Average	501
Greece	513	Cyprus	494
Sweden	512	Latvia	488
Canada	509	Switzerland	488
International Average	501	Greece	486
Italy	474	Canada	485
Czech Republic	469	France	466
Germany	465	Czech Republic	451
United States	442	Austria	435
Austria	436	United States	423

Table 4: International Math and Physics Performance

After results of this test were released, the U.S. Department of Education released a number of statements that can be found online at (Archived US Dept. Education TIMSS Responses). One statement contained the following:

Today's release of 12th-grade results shows that U.S. students' standing relative to other TIMSS countries continues to decline in the high school years. A comparison of U.S. 12th graders' general mathematics and science knowledge to students in 20 other nations shows that our students scored below the international average in both topics and exceeded the performance of only two nations. A separate examination of advanced mathematics and physics comparing our students taking pre-calculus or calculus and our students taking physics with advanced mathematics and physics students in other nations shows that the performance of our advanced students is among the lowest of countries participating in TIMSS.

Of 21 countries, the only two that the U.S. "significantly outperformed" in mathematics were Cyprus and South Africa.

These reports state that this was not a case of high-achievement among some and poor achievement among others. It states that "the entire distribution of U.S. scores is shifted downward from that of many of the high performing countries."

Another release put out by the National Center for Education Statistics stated that:

TIMSS showed very low results for US students compared to those in the other countries giving the tests, both for general knowledge by average graduating seniors and for advanced performance by seniors studying physics and calculus. A recent report, *Facing the Consequences*, from the US TIMSS Research Center suggested that these results were certainly to be expected. It pointed out that there was a consistent decline in our relative standing from fourth grade to eighth grade in both mathematics and science. Of the almost 40 topics examined in both mathematics and science, none showed improved standing relative to other TIMSS countries from fourth to eighth grade. Most topics showed a decline over the middle school years.

Schmidt said, "It could hardly be a surprise to find this decline continuing on through high school. As we discussed in *Facing the Consequences* and in our earlier report *A Splintered Vision*, US curricula through eighth grade do not focus on any key topics or give them significantly more attention. Those curricula and our textbooks are highly repetitive and unchallenging in grade after grade of the middle school years. How could they provide a sound foundation on which to

build during the high school years?" The middle school curricula in most TIMSS countries cover topics from algebra, geometry, physics and chemistry. For most US students these are first studied, if at all, in high school. Many students (about 15 percent) never study algebra, geometry (about 30 percent), advanced algebra (40 percent), other advanced mathematics (around 80 percent), chemistry (about 45 percent) or physics (almost 75 percent).

Schmidt indicated, "US students frequently opt out of advanced study of mathematics and science in high school or are placed in less demanding courses even if they do continue to take mathematics and science courses. So high school mathematics and science is unlikely to overcome the poor foundation provided during US middle school education and reverse the downward trend in comparative performance for average students."

Since the initial test, U.S. students have scored marginally better, but international scores have also risen, meaning that U.S. relative rank has not moved appreciably.

2.6.2 A Side-Note on Biological and Agricultural Sciences

Unlike engineering, the number of people entering the biological sciences has grown significantly since 1985 despite the fact that biologists and agricultural scientists are paid much less than other types of STEM workers. This difference is so great that the National Science Board has recognized a significant bifurcation between wage level, benefits, and career opportunities for those in life-sciences and those in chemistry, physics, mathematics, computer sciences, and engineering. (National Science Board, 2004) Despite the obvious economic benefit of going into the "dead"-sciences, an increasing number of STEM inclined people are choosing those professions which offer the least economic reward instead. One difference between biological sciences and the others just mentioned is that organic systems are much more complicated than systems studied or created by other STEM workers. Because biological systems are less well understood, the learning content of a biological education today focuses more on descriptive rather than normative theories and requires relatively more statistics than calculus. Whereas an introductory physics course forces students to learn theories, rules, and principles, introductory biology classes must focus more on memorization of large bodies of knowledge. Physicists and engineers generally must study mathematics through differential equations, linear algebra, and beyond. In contrast, most biology undergraduate programs require only one semester of calculus. The fact that more people inclined towards STEM choose biology today rather than engineering may result partially from weaker confidence in the types of mathematics with strong sequential dependencies. As biology becomes increasingly focused on computation, this may change.

2.6.3 Teacher Quality: Primary Determinant of Student Performance

If American performance in STEM subjects at the K-12 level is so poor relative to other countries, the obvious question is: "Why?" A variety of studies have found that when other factors are controlled for, student outcomes correlate very strongly with the characteristics of individual teachers. Schater and Thum note that "[i]n the last decade, a series of studies has confirmed that access to an effective teacher is

the single most school related factor responsible for increased learning.” They state that “[w]hen compared to virtually every other school reform effort to date (e.g. class size reduction, charter schools, vouchers, direct instruction, technology, etc.), students who have effective teachers achieve the most.” (Schater, et al., 2004) In fact, high quality educators have even been found to mitigate many of the effects of negative socio-economic influences such as poverty. Schater and Thum find that “[q]uality teaching produced a 0.91 standard deviation gain in students’ achievement, which approaches mitigating the effects of students’ home environment (1.61), prior knowledge (0.92), or parental income (0.67).” (Schater, et al., 2004) Hanushek notes that “a good teacher will gain one and a half grade-level equivalents whereas a bad teacher will get a gain of only half a year.” (Hanushek) Rockoff finds that “A one-standard-deviation increase in teacher quality raises test scores by approximately 0.1 standard deviations in reading and math on nationally standardized distributions of achievement” (Rockoff, 2004) Rivkin, Hanushek and Kain find that “moving from an average teacher to one at the 85th percentile of teacher quality (i.e., moving up one standard deviation in teacher quality) increases student achievement gains by more than 4 percentile ranks in the given year. With their data, this is roughly equivalent to the effects of a ten student (approximately 50%) decrease in class size.” (Rivkin, et al., 2005) Teacher quality is a higher leverage point than student-teacher ratio, per-pupil spending, or any other school-related lever.

2.6.4 What Is Teacher Quality?

Given the importance of teacher quality on student outcomes, it is logical to ask what teacher quality is and how it is measured. Teacher quality at the individual level is easy to observe but nearly impossible to quantify because teaching is a creative and entrepreneurial endeavor. As is the case for most knowledge workers, reliable objective metrics for teacher quality are hard to create and gather. A large portion of the attributes that make a teacher effective are subjective in nature. Teaching is fundamentally different from rote-tasks such as assembly-line work, and attempts to impose simplistic formulas to gauge performance are an insult to the educational profession. Many economists therefore simply risk tautology by defining teacher quality as that which causes a relative improvement in students' performance over time. Hanushek and Rivkin call this “outcome-based measures of quality.” They have written a very good summary of the current state of research on teacher quality as chapter 18 of the *Handbook of the Economics of Education*. (Hanushek, et al., 2006) In this work they summarize the current state of research attempting to determine the impact that teacher, school related, and socio-economic parameters have on student outcomes. As discussed in the previous section, an emerging consensus has determined that teacher related attributes are much more significant than school related attributes, and can even mitigate much of the impact of socio-economic impacts on student outcomes. These researchers have focused in on which teacher related attributes can be found to correlate with student outcomes, and which have no impact. Disambiguating the individual impacts of all of these factors is an enormous statistical undertaking. Creating a better understanding teacher quality requires triangulation between imperfectly measurable teacher attributes and imperfectly measurable student performance indicators in an attempt to determine which correlations from one set have the most significance when mapped to the other. These studies recognize that attributes correlating with teacher quality are only *proxies* for teacher quality. No metric or set of metrics can accurately capture the quality of an individual teacher. Knowing the values of each significant proxy for an individual teacher may give a very poor indication of how good that person is in the classroom. In the aggregate however, these attributes can have a high degree of correspondence

with student outcomes. As a school administrator, knowing the averages for important teacher related proxies would be a very good way of predicting student outcomes in that school.

As a side note, when studying teacher quality and student outcomes, or when trying to improve either, it is extremely important not to rely on imperfect metrics in inappropriate ways. Doing so can actually degrade quality by encouraging educators to cheat their students out of a quality education by simply “teaching to the test” all year. Imperfect measures of teacher quality can cause teachers’ career growth to be tied to a series of meaningless rituals that have no bearing on the needs of their students. Such metrics do much more to deter good people who might otherwise switch careers into teaching than they do to raise the quality of the current stock of teachers. For instance, Angrist and Guryan actually found a negative correlation between SAT score and PRAXIS II pass rates. (The PRAXIS II is a test widely used in teacher certification.) This was found because teaching candidates that have not gone through teacher education programs had higher SAT test scores than candidates that had gone through those programs. (Angrist, et al.) They go on:

Recent years have seen an acceleration in the use of standardized tests to certify teachers. Proponents hope these measures will increase quality, but economists have long been skeptical of entry barriers that may shift supply and discourage otherwise qualified applicants. Tests interact with the American system of teacher education since many teacher-education programs focus on getting students certified. Although students of accredited and other teacher-education programs do better on the widely used Praxis test, our estimates show no impact of testing on the type or affiliation of teachers' undergraduate program or school. This is perhaps desirable if teacher-education programs are seen as insufficiently rigorous. On the other hand, there is also no evidence that testing hurdles have raised the quality of new and inexperienced teachers, at least as measured by undergraduate background.

(Angrist, et al.)

2.6.5 Judging the Proxies for Teacher Quality

This section will discuss which measurable teacher attributes have been found to correlate with teacher quality and which have not. Unless otherwise noted, the information cited in this section has been drawn from (Hanushek, et al., 2006). Studies have shown that the subjective opinion principals have of teachers have been found to correlate very closely with objective measures of their students’ educational outcomes. (Rockoff, 2004) Other indicators that have been found to have higher correlations with student outcomes and are more often studied include teacher performance on standardized tests such as the SAT, ACT, or GRE. Many researchers cited in these and other studies assume that teacher quality is also highly correlated with selectivity of the teacher's undergraduate institution and significant subject matter expertise (Figlio, 1996), the teacher's college grades, and the teacher’s college class rank. These indicators of teacher quality are harder to do studies on however both because of a lack of data and because college grades and class rank may not be objective measures. Results may be skewed by the fact that classes offered in teacher education programs may have different levels of rigor than university courses offered in other fields. Their quality may also change over time. It is therefore impossible for studies that rely on the use of data-mining within large sample size databases to produce reliable

measurements in these cases. Ultimately, it is taken for granted by many that better students make better teachers. These findings should not be very surprising.

Years of teaching experience have been found to have a weak non-linear correlation with a quality. A characteristic “learning curve” pattern has been found in some cases. One peculiar study found a normal learning curve in vocabulary skills, but a learning curve with significant drop-off in the case of math computation. This unexplained result showed that math teachers with three years of experience were significantly better than first year math teachers, but teacher with nine years of experience were no better than first year math teachers. Teacher quality in this study appeared to degrade over time after the three year mark. (Rockoff, 2004)

Master’s degrees have been found to have no correlation with quality. Salaries have been found not to correlate with quality. Teacher certification only has a minimal correlation with quality. There is no quality difference between teachers with full certifications and those with emergency certification. Additional teacher training also has virtually no impact on student outcomes.

2.6.6 Teacher Quality in Decline

While it is impossible to track the abstract notion of ‘teacher quality’ over time, proxies that correlate with it can be tracked in an attempt to pick up on observable trends. Many researchers tracking these proxies have stated that teacher quality has declined significantly since the 1950s and experienced the steepest drop during the 1970s and 1980s. (Hanushek, et al., 2002). Teacher quality in the 1940s and 1950s was quite high. Over 50 percent of teachers scored above the 80th percentile on various standardized tests including IQ tests. By the 1970’s this percentage had fallen to 30 percent, and by the 1990’s it had fallen to 8-9 percent. (Bacolod, 2007) Observable drops in undergraduate GPA, class rank, selectivity of undergraduate institution, and scores on standardized tests including the SAT, GRE, and ACT have occurred over the course of this time period. Whereas teachers 50 years ago tended to be at the top of their class, today, the SAT score of the typical teacher tends to correspond with a C+ average GPA. (Angrist, et al.)

2.6.7 Teacher Qualification

In addition to general characteristics of a teacher's school and test-taking performance, another obvious aspect of teacher quality is preparedness to teach a particular subject. The heaviest teacher shortages exist in STEM subject areas. Consequently, STEM subjects are most likely to be taught by those unqualified to teach them. *Rising Against the Gathering Storm* presents the following table and speaks to its content (NAE, 2007 p. 115):

TABLE 5-1 Students in US Public Schools Taught by Teachers with No Major or Certification in the Subject Taught, 1999-2000

Discipline	Grades 5–8	Grades 9–12
English	58%	30%
Mathematics	69%	31%
Physical science	93%	63%
Biology–life sciences	—	45%
Chemistry	—	61%
Physics	—	67%
Physical education	19%	19%

SOURCE: National Center for Education Statistics. *Qualifications of the Public School Teacher Workforce: Prevalence of Out-of-Field Teaching 1987-1988 to 1999-2000*. Washington, DC: US Department of Education, 2003.

Table 5: Percentage STEM Classes Taught by Unqualified Teachers

In the worst instance, sixty seven percent of physics classes are taught by teachers unqualified to teach the subject. Of all STEM subjects, mathematics has the highest percentage of classrooms taught by teachers certified in the field. What may be masked in this statistic however is the fact that many math teachers have degrees in “Mathematics Education” rather than “Mathematics”. These segregated programs may produce teachers that are less capable in the subject than programs not specifically tailored for people intending to enter the teaching profession.

Rising Against The Gathering Storm states that:

Today there is such a shortage of highly qualified K–12 teachers that many of the nation's 15,000 school districts have hired uncertified or underqualified teachers. Moreover, middle and high school mathematics and science teachers are more likely than not to teach outside their own fields of study. A US high school student has a 70% likelihood of being taught English by a teacher with a degree in English but about a 40% chance of studying chemistry with a teacher who was a chemistry major.

These problems are compounded by chronic shortages in the teaching workforce. About two-thirds of the nation’s K–12 teachers are expected to retire or leave the profession over the coming decade, so the nation’s schools will need to fill between 1.7 million and 2.7 million positions during that period, about 200,000 of them in secondary science and mathematics classrooms.

We need to recruit, educate, and retain excellent K–12 teachers who fundamentally understand biology, chemistry, physics, engineering, and mathematics. The critical lack of technically trained people in the United States can be traced directly to poor K–12 mathematics and science instruction. Few factors are more important than this if the United States is to compete successfully in the 21st century.

(NAE, 2007 p. 113)

Based on the above discussion it is necessary to consider two separate kinds of secondary school teacher quality: that which makes someone a good educator in the general sense, and that which makes someone qualified to teach the subject they are charged with. It is likely that many students have a poor teacher who knows a STEM subject reasonably well or an exceptional history teacher attempting to teach physics. Neither will be effective.

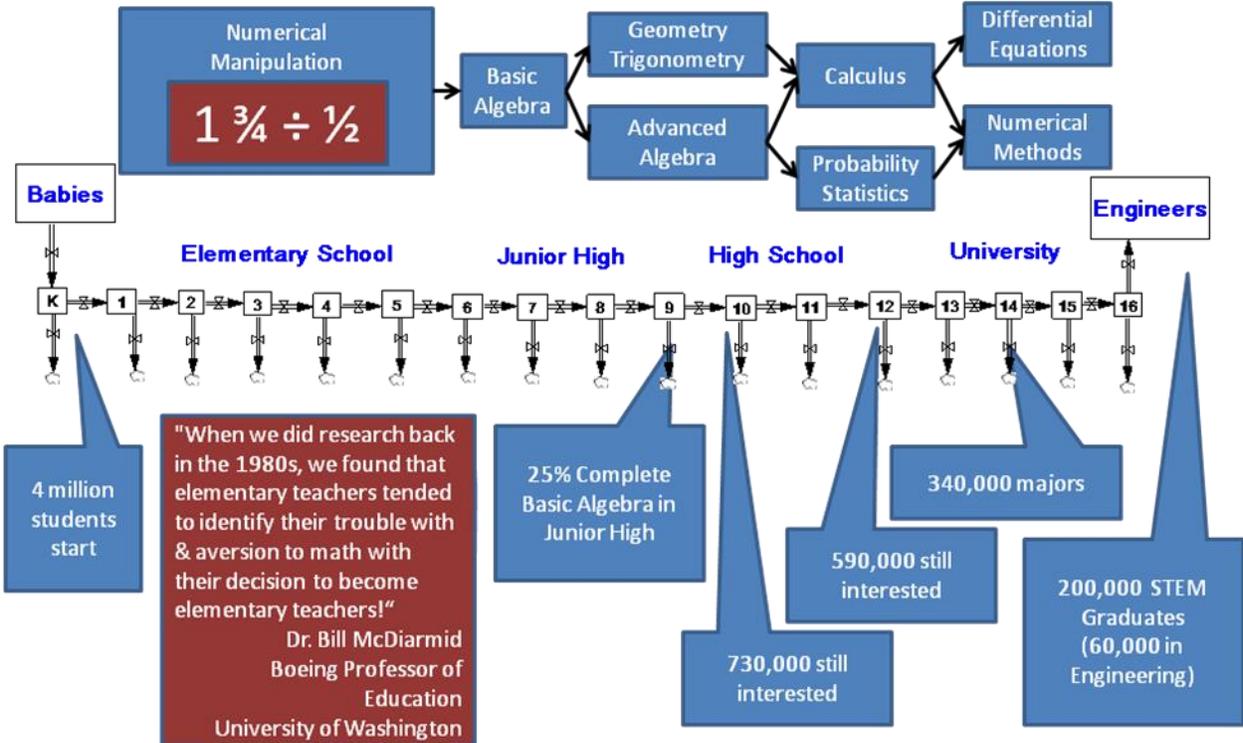


Figure 21: STEM Gauntlet Highlighting Elementary School Deficiencies

Finally, it is crucial to recognize the role played by elementary level teachers during formative years when basic numerical concepts must be mastered and interest in varying subjects is either encouraged or squashed. The elementary school teacher is thought to be a generalist who understands early childhood development and is also competent to teach all subjects at a rudimentary level. While not a subject matter expert in STEM, this individual should be able to teach basic math and science subjects in a thorough and compelling way to give students a foundation on which to build. Unfortunately, according to Dr. Bill McDiarmid, Dean of the College of Education at UNC Chapel Hill, "we found that elementary teachers tended to identify their trouble with & aversion to math with their decision to become elementary teachers!"

Only 43% of a sample of elementary school teachers in a recent study could correctly simplify the following fraction:

$$1 \frac{3}{4} \div \frac{1}{2}$$

(Note: The answer is 3.5.) This numerical manipulation skill is something that is supposed to be taught in the 4th or 5th grade. Furthermore, only 10% of those teachers could adequately explain what it meant conceptually to divide by a fraction or give a real-world example. (Ma, 1999) (The same study found that 100% of Chinese elementary school teachers, with the equivalent of only a junior high school education and two years of normal school, could solve the same problem and 90% had a strong grasp of the conceptual underpinnings behind this and other math problems.) Because it is unreasonable to expect children to master concepts that their teachers have not, it is logical to assume that a large fraction of American students have fallen out of the STEM pipeline before they reach the age of 12 and enter junior high school.

While it is certainly not necessary for an individual teaching elementary school students to have completed a STEM degree, it seems reasonable to assume that to effectively teach a subject an individual should have mastered material at least one conceptual step above that which is being taught. Someone teaching numerical concepts in elementary school should have a thorough grasp of basic algebra. Someone teaching basic algebra should have a thorough grasp of geometry, trigonometry and advanced algebra or pre-calculus. The purpose of mastering material at least one step ahead of what is being taught is that this ensures that the educator has not only an algorithmic foundation (deductive knowledge, or knowledge the rules of symbol manipulation), but also understand the subject conceptually (inductive knowledge, can derive the rules from real-world examples and experiences). A conceptual understanding of material is essential to being adaptive in the classroom, to designing pedagogical experiences that inspire interest in students, and to effectively communicate the relevance of the material to their lives. The devastating fact that Ling Ma demonstrated is that many of today's elementary school teachers may themselves have fallen out of the STEM pipeline in elementary school. McDiarmid stated that they later used this fact a basis for deciding to become elementary school teachers themselves.

A recent paper by Grishmore, Hurtig, and Farbrother analyzes the educational pipeline as a control system and statistically estimates the impact of investment in improving pipeline retention at different education levels. (Grismore, et al., 2003) They did this to determine where effort should be focused to

maximize the number of STEM workers that emerge at the end. The conclusion was that focus on the earlier years – elementary and junior high – would most significantly impact on the number of people leaving college with a STEM degree.

2.6.8 Student Behavior: Where Ability Meets Intent

The model so far is a very crude representation of human motivation. Although this “rational-actor” caricature is true if all else is held equal, this assumes that other important forces besides the lure of future economic wealth do not cause the system to move in other interesting directions.

Ajzen and Fishbein’s “Theory of Reasoned Action” (TRA) (Ajzen, et al., 1980) and Ajzen’s “Theory of Planned Behavior” (Ajzen, 1985) offer some guidance on how to proceed when developing the model further. These mathematical formulations from the field of social psychology attempts to tease apart and separately represent the factors that can influence individual and aggregate behavior so that it is more predictable. These theories structure multi-attribute utility equations inside matrices representing different determinants of behavioral intention.

TRA differentiates between the individual’s attitudes toward a behavior and that same individual’s beliefs about social norms held by others. The probability that a person will perform some action can be predicted by understanding both their different beliefs about the positives and negatives associated with that behavior, and their beliefs about how other people they deem important will judge them should they take that action. This theory has been found to be a very good predictor of future actions in situations when the individual has a high degree of control over the outcome. It has been found to have less predictive ability in such situations when the individuals have less than perfect control over the outcome.

TPB was developed in response to the weaknesses in TRA. TPB is a superset of TRA that takes into account how much perceived behavioral control a person has over that behavior in addition to attitude toward behavior and belief about social norms. Studies using this formulation have been found to be very good predictors of individual and group behavior in studies of smoking cessation, the use of birth control, and academic performance.

At the highest level, these theories can be expressed thusly:

- Behavior is a function of *Perceived Control* and *Intent*
- Intent is a function of *Personal Attitude* and *Belief about Social Norms*

TPB offers a more realistic way of understanding behavior and intent than the “rational actor” formulation of student motivation presented so far. For instance, in the survey results described in (Grismore, et al., 2003), students displayed a declining *interest* in pursuing a STEM career over time. A student who was interested in junior-high school but who is no longer interested in high school could be reporting a lack of interest due to many things that could have happened in the intervening time period. This student could have done poorly in a class due to lack of effort or bad instruction, thus reducing perceived behavior control. The same student could have decided that other subjects were more interesting or heard that you can make more money in other fields, thus altering personal attitude. The effects of various considerations that might influence a student’s decision to leave the STEM pipeline are hard to disambiguate. What is clear is that a loss of perceived control will often mask itself as declining interest or intent. While the system dynamics model presented here will not incorporate the theory of planned behavior in its formulation, it will incorporate aspects beyond a simple “rational-actor” formulation in determining student outcomes.

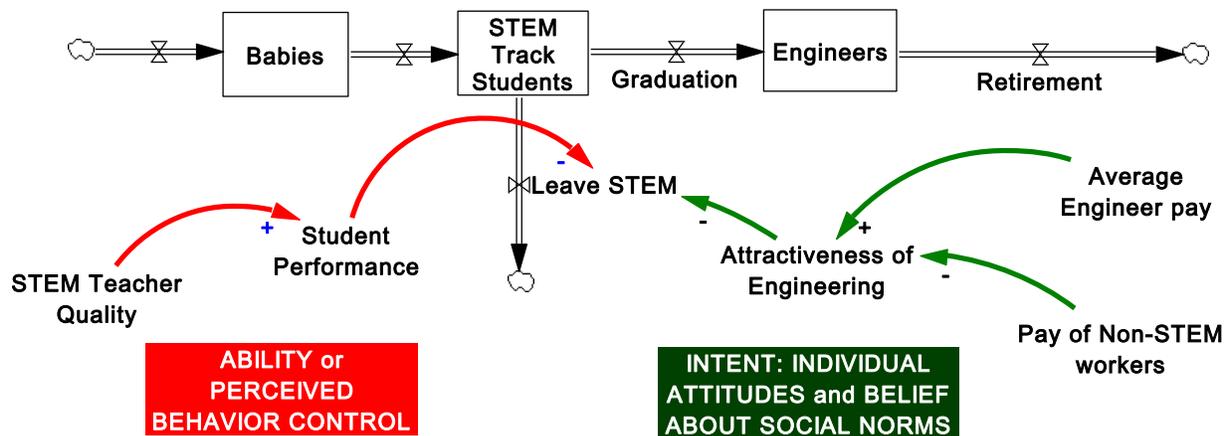


Figure 22: STEM Student Ability and Intent Conceptual Structure

This conceptual model determines a student’s probability of falling out of the STEM pipeline by combining the influence of two factors:

<i>Ability or perceived control</i>	Quality of instruction in STEM subjects. Studies of student outcomes have found that the quality of the educator has more influence on student success than all other factors influencing the educational environment. High quality instructors have even been found to alleviate other factors outside the school such as a negative home environment.
<i>Individual attitude and social norms</i>	Belief about economic payoff based on current market conditions. An older student in high-school or college may consider these influences directly. A younger student may experience this influence indirectly through parent or community influences. Quality educators will also influence individual attitudes because they can make the subject more engaging and seem more relevant to the life of the student.

Table 6: Tracing Perceived Control, Attitudes, and Social Norms

This model is still simplistic and could be expanded in the future to incorporate other social factors to improve its realism. It is believed however, that the two influences currently expressed in the model are some of the strongest factors influencing student behavior either directly or indirectly. Furthermore, I believe that while additional detail complexity may help with point predictions, it is unlikely that other factors that influence pipeline retention will be found to have a strong negative correlation with either teacher quality or financial reward. If anything, additional detail may further strengthen the loops that will be explored below.

2.6.9 Determinants of Teacher Quality

2.6.9.1 Current and Historical Teacher Pay

The obvious first place to look when exploring why the U.S. has low quality teachers on average is to look at teacher pay. The same chart shown above demonstrating that engineers and computer scientists

have the highest salaries in the U.S. also shows that educators have the lowest average yearly earnings of all college graduates. Although they start slightly higher than those with degrees in arts and humanities, increases over time do not keep pace, and salaries after ten years are almost ten-thousand dollars below the next highest paid degree type (NCES, 2008):

Salaries of full-time employees by degree type and number of years since degree earned			
	1-2 years (1994)	4-5 years (1997)	9-10 years (2003)
Total	\$30,800	\$39,900	\$60,600
Engineering	38,900	51,400	74,900
Computer science	33,400	50,400	72,600
Business and management	33,800	43,400	65,900
Health	40,500	45,600	65,000
Biological sciences	29,200	33,900	62,200
Mathematics/physical sciences	27,100	37,800	58,200
Social and behavioral science	26,900	39,200	62,300
Arts and humanities	25,000	33,600	52,800
Education	26,600	31,700	43,800
All STEM fields	33,800	45,600	68,300
Non-STEM fields	30,200	38,800	58,900

Table 7: Salaries by University Degree Type and Year since Graduation

Low teacher pay is an extremely plausible reason for low quality in the average K-12 educator. We must also explore why there was such a decline in average teacher quality since the 1950's. The following chart shows a rapid decline in teacher wages relative to other professionals with college degrees. In the 1940's both men and women could expect to earn more than the average college graduate if they chose to teach (Hurley):

Teacher pay premium (or penalty) relative to other college educated workers			
Year	Male	Female	
1940		3.60%	15.80%
1950		-2.10%	11.20%
1960		-19.70%	12.70%
1970		-33.10%	3.10%
1980		-36.10%	3.70%
1990		-37.50%	-4.50%
2000		-60.40%	-16.40%

Table 8: Teacher Pay Decline over Time

Today, the financial penalty is sixteen percent for females and 60 percent for males. However, this aggregate level data does not take into account pay differentiation by non-teaching field. The opportunity cost of an engineer or computer scientist choosing to teach may be in the range of eighty to one hundred percent.

2.6.9.2 Gender Related Mobility

Another reason quality may have dropped over the course of this time is that liberalization of gender roles opened opportunities for college educated women beyond the more traditional choices of teaching, nursing, and social work. In the 1940's, 1950's, and 1960's the labor market for teachers operated somewhat independently of the labor market in industry. The economist Peter Temin pointed out that because women were a trapped labor pool, the wages of female teachers were compared against the wages of other jobs available to women when making career choices. (Temin, 2002) As previously pointed out, female teachers earned wages that were 15% higher than other choices available to college educated women. These female teachers went to college and entered the workforce at a time when many women did not. This means that they may have been somewhat more progressive people with high motivation and entrepreneurial tendencies. Studies indicate that these women were very likely to have IQ scores above the 80th percentile. According to Temin, this market operated efficiently and cleared based on the quality rather than quantity of women in the labor pool. Schools could draw upon the best and brightest of 50% of the American population without directly competing with industry STEM wages.

The figure below has been drawn from *The Economics of Labor Markets* by Kaufman and Hotchkiss (Kaufman, et al., 2006). It was created to describe what happened to the teacher labor market in the 1970's. The book relates that in the late 1960's and early 1970's, a large influx of women entered college because of the demographic hump created by the 'baby-boom' and an increased percentage of women that went to college due to gender role liberalization. During this transition period many of these women got degrees leading towards jobs in traditionally female dominated careers such as teaching. In the early to mid seventies, the K-12 age group shrank as the baby-boomer presence in that demographic faded. Suddenly, there was a glut of potential teachers without classrooms. Wages of teachers began to drop relative to other jobs in the economy as a result. The number of new teachers began to fall, thus bringing supply and demand back into balance. According to Temin, the result was that market for teachers began to clear based on quantity rather than quality. While it was not stated in the text this figure was drawn from, I believe that the relative teacher wage depression in the 1970's combined with newly available STEM career paths for women, caused succeeding cohorts of new teachers to have dramatically lower average quality.

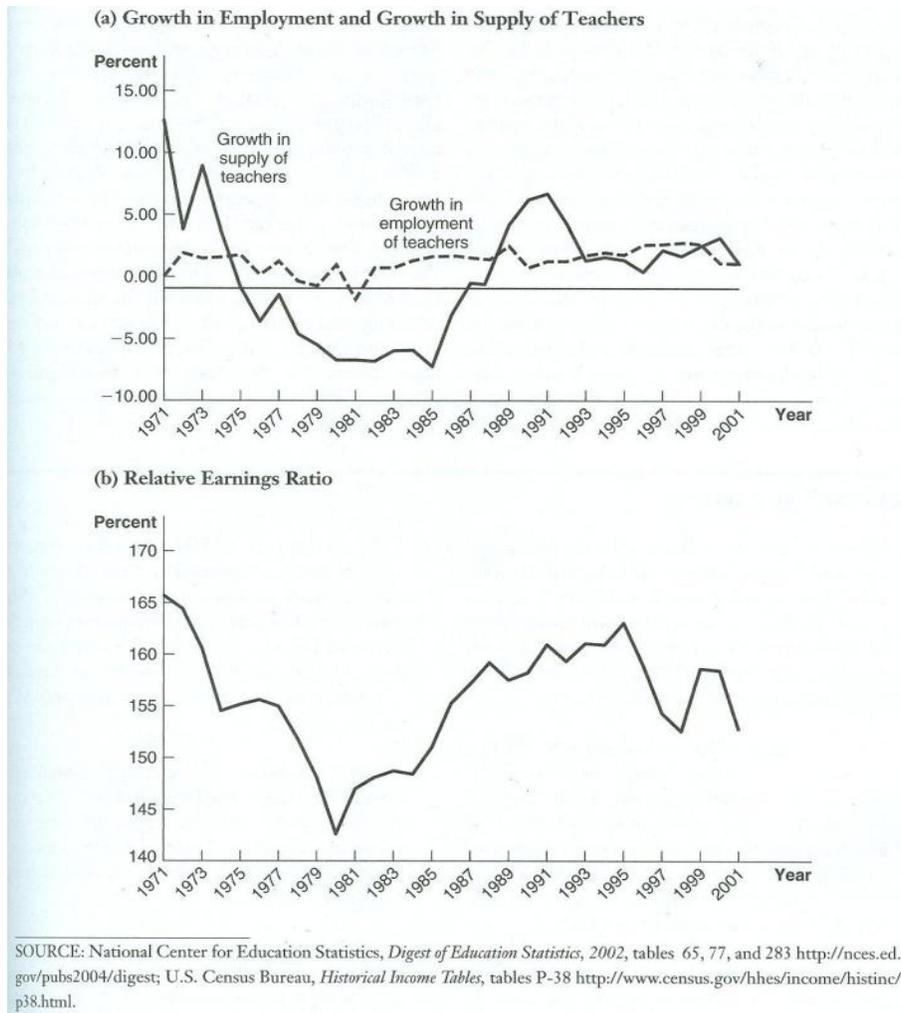


Figure 23: Teacher Supply and Demand and Relative Earnings

As shown previously in Figure 14, there was period from 1975 to 1985 in which a massive influx of women earned Bachelor's degrees in engineering. Prior to this point, these STEM interested women may have chosen to become science and math teachers, but the labor markets for STEM teachers and workers were now becoming integrated. Many of these women would likely end up in industry for the first time.

Temin discusses at length the impact of this transition on how the system operates today (Temin, 2002):

We are not paying teachers enough to get high-quality applicants. The result is that reforms have little effect because teachers are limited in their effectiveness.

We are sub-optimizing with the current stock of teachers, rather like the short-run adjustment of a firm with a fixed capital stock. Current reforms of school administration and evaluation take the quality of teachers as given; they simply rearrange the existing educational assets and have little or no effects. Only when we break out of the current equilibrium of

pay and quality will education in the United States show a marked improvement.

Low pay yields low quality. We traditionally ran our schools using a trapped labor force, but we have liberated women in the past generation. We have not been willing to pay enough to attract high quality teachers in an open market.

We have substituted quantity for quality as the supply price of high-quality female teachers rose. These interpretations are supported by models with unique equilibria.

We rationalize the status quo...

We are at a local optimum, but far from the global optimum. The low quality of current teachers has locked us into an equilibrium that is inferior to one we might have reached with a different history. In other words, we have not accommodated to the changing labor force participation of women in the best way for education.

2.6.9.3 Teacher Incentive Structure

Beyond looking merely at the pay of teachers in the aggregate, it important to look at the incentive structure determining the compensation of individual teachers and how it impacts teacher quality.

Unfortunately it appears that the incentive structures in the teaching profession are severely misaligned. (Schacter, et al., 2004) Teacher pay has been found to correlate almost entirely with years of tenure, hours of teacher training, and additional teacher education. While these metrics have almost no bearing on outcomes, they are used almost exclusively in determining pay and career advancement. (Sander, 2008)

Other proxies for teacher quality such as the subjective opinion a principal has of the teacher's performance, the undergraduate grades of the teacher, the selectivity of the teacher's undergraduate institution, the teacher's scores on such tests as the SAT, ACT, or GRE, and the teacher's expertise in the field they are teaching have no bearing on the teacher wages. (Southwick, et al., 1997) Earlier it was noted in (Hanushek, et al., 2006) that teacher pay was not correlated with teacher quality. ***This is because pay is not correlated (and in some cases is negatively correlated) with all teacher attributes that have been found to significantly correlate with student outcomes.***

However, those attributes which correlate with student outcomes also correlate highly with potential industry pay. This simply indicates that those who tend to make the best teachers also tend to be very good at other things as well. Because teachers are knowledge workers, and because knowledge workers became much more valued in recent history, the correlations linking student outcomes and higher potential industry pay became much stronger over the past fifty years. Simultaneously, union work rules dramatically decreased the influence of those same factors in determining individual teacher wages. The most capable teachers therefore experience the largest opportunity cost because they experience the largest gap between their teaching salaries and their potential industry pay.

Also notable is the fact that teacher pay is not in any way correlated with subject area being taught. STEM teachers are paid no better than history or art teachers. While teacher pay varied more widely in the 1940's and tended to be set individually based on the discretion of principals and school boards, today it is highly regulated by union rules according to a "uniform salary schedule" that attempts to be "objective" and causes salary compression. (Southwick, et al., 1997)

Southwick and Indermit note that there has been a "decline in the quality of math and science teachers. This ... is largely caused by the practice of paying teachers according to a salary schedule based only on the number of credits beyond a Bachelor's degree and the number of years of teaching experience. This "unified salary schedule" does not take into account the teacher's specialty; a mathematics or physics teacher will be paid the same as an English or social studies teacher who has the same number of years of schooling and years of experience." They go on to say that "while this system is not of recent vintage, having been in place for most of this century, its effects are increasingly serious in an economy that is becoming more technical. Between 1985 and 1991, the salaries of teachers rose by about 5.5% per annum, while salaries in mathematically oriented professions (e.g. accounting, computer systems analysts, engineers) rose by more than 6% per year, and salaries in verbally oriented professions (e.g. advertising, copyreaders, editors) rose by about 4.5% per year. This implies that qualified teachers in mathematics and sciences may be becoming increasingly more difficult to attract than are teachers in other subject areas."

Southwick and Indermit conclude that "If the trend continues, the U.S. will tend to become a nation which can speak and write well but which increasingly has less to say and write about subjects which rely on quantification." (Southwick, et al., 1997)

2.6.10 Summary of Literature on Incentive Structure in Teaching Profession

The next chart distills the previous discussion by placing the relationships between teacher attributes and their influence on teacher pay, their influence on STEM student outcomes, and their relationship with potential pay available outside of teaching into a single chart. Green boxes indicate correlations, yellow indicates a tenuous relationship, and clear indicates no or slightly negative correlations:

Correlation between various teacher attributes and teacher pay, student outcomes and opportunity cost			
Teacher Attribute	Teacher pay	STEM Student Outcomes	High Industry Pay
Number of years in teaching	Green	Yellow (Learning curve)	White
Additional teacher training	Green	White	White
Masters degree in education	Green	White	White
Subjective opinion of boss (principal)	White	Green	Green
Undergraduate GPA	White	Green	Green
Selectivity of undergraduate institution	White	Green	Green
SAT or ACT test scores	White	Green	Green
Subject matter area test scores	White	Green	Green
Expertise in STEM subject matter	White	Green	Green
Mobility (social and geographic)	White	White	Green

Table 9: Correlation between Pay, Quality, Opportunity Cost, and Other Teacher Attributes

It should be no surprise that teacher attributes which are meaningful proxies for teacher quality including undergraduate GPA, selectivity of the teacher’s undergraduate institution, test scores, and subject matter expertise in STEM have all declined dramatically in recent history. Teachers continue to be rewarded based on metrics that have no correlation with student outcomes. Those proxies for teacher quality which have a good deal of predictive power also have a high degree of correlation with potential industry pay, and thus the opportunity cost an individual faces when choosing whether or not to enter the teaching profession in the first place.

Two anecdotes artfully illustrate the dilemma we face:

- In the spring of 2008 it was announced that four AP courses would be cut from the portfolio of classes that allow advanced high-school students to earn college credit. These courses were Italian, Latin Literature, French Literature and AB Computer Science. The decision to cut these courses came about because few schools offered them. According to a Washington Post article reporting on the issue, many school systems did not offer these courses because they wanted to be “more focused on core subjects.” (de Vise, 2008). While this is a plausible argument for the

three language courses listed, it seems ridiculous in the case of computer science. While some may mourn the other three course offerings that were removed, I would argue that few high school subjects have a more potential to teach skills valued in the global economy than computer science. It is extremely doubtful that parents or children are uninterested in earning advanced placement in that field. I suspect that the real reason this course was offered in so few schools is because not many qualified teachers could be found to teach the material. The subject is ideally taught by those with computer science, electrical engineering, or math training. Dr. Lenore Blum, Professor of Computer Science at Carnegie Melon University, has said that in many schools it is treated as a trade school subject and taught by people with business backgrounds or no related background at all however.

- Marvin Minsky, a founder of the field of Artificial Intelligence, relayed a story to me about something that happened in a Boston area school district in the 1980s. A large high-tech firm decided to do a good deed for the local community by offering free summer-time training in computer programming to the local math teachers so that they could bring this new knowledge into the classroom. The result was that a large portion of those teachers found programming jobs and quit. The schools were left without their math teachers. *Teacher training that is effective at improving teaching quality will also increase turnover if pay is not increased to match.*

2.7 Fourth Conceptual Model: Teacher Quality Loop

Based on the above discussion, the conceptual model will now be expanded to contain another feedback loop that may allow the model to more accurately represent the real-world system.

2.7.1 Teaching Wages and Teacher Quality

Before describing the functioning of that new loop however, it will be best to first describe the relationship between teacher wages, industry wages, and new STEM teacher quality in the model. This mathematical relationship is depicted below:

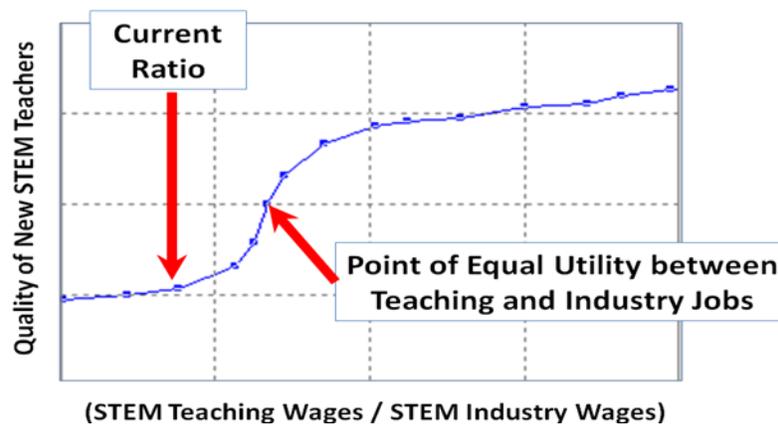


Figure 24: Function Defining Relationship between Teacher Wages and New Teacher Quality

The ratio of stem wages to industry wages is plotted on the X axis above. The point at $X=1$ is the point at which teaching and industry jobs have equal utility. This lookup table resembles a ‘sigmoid’ function. Quality is very sensitive to pay in the region where the two utilities are fairly equal. Quality is less sensitive to pay if one job is significantly different from the other in terms of compensation. For example, if the average computer scientist could earn \$100,000 and a teaching job is worth \$50,000 then this ratio will be 0.5. Increasing the pay to \$55,000 will increase the ratio to 0.55. Because 0.5 and 0.55 are in an insensitive region of the graph, this change will not appreciably improve the quality of new entrants. On the other hand, if the outside pay potential of history teachers is \$50,000, the ratio for them will be 1. A movement from 1 to 1.1 will cause new entrants to have higher quality because this shift occurs in a steeper region on the graph. It is therefore probable that a small increase in teacher wages today will positively impact the quality of new humanities teachers much more than new STEM teachers.

Unlike the balancing loop presented before, this is a positive or reinforcing feedback loop. Reinforcing loops are responsible for rapid periods of change that can destabilize systems by creating exponential growth or decay. Positive feedback loops are capable of moving in two directions. The one just described is a vicious cycle. In the other, more virtuous direction, (if teaching quality were high enough that enough STEM workers were being produced) teacher quality would continually grow, engineers would proliferate, and engineering wages would be low. Neither of these extreme scenarios would occur in reality because many other loops exist to limit the exponential growth or decay caused here. However, the existence of this loop can serve to defeat reform that is too weak to 'tip' its behavior to operate in the opposite, more virtuous direction.

2.7.3 Teacher Quality Determinants

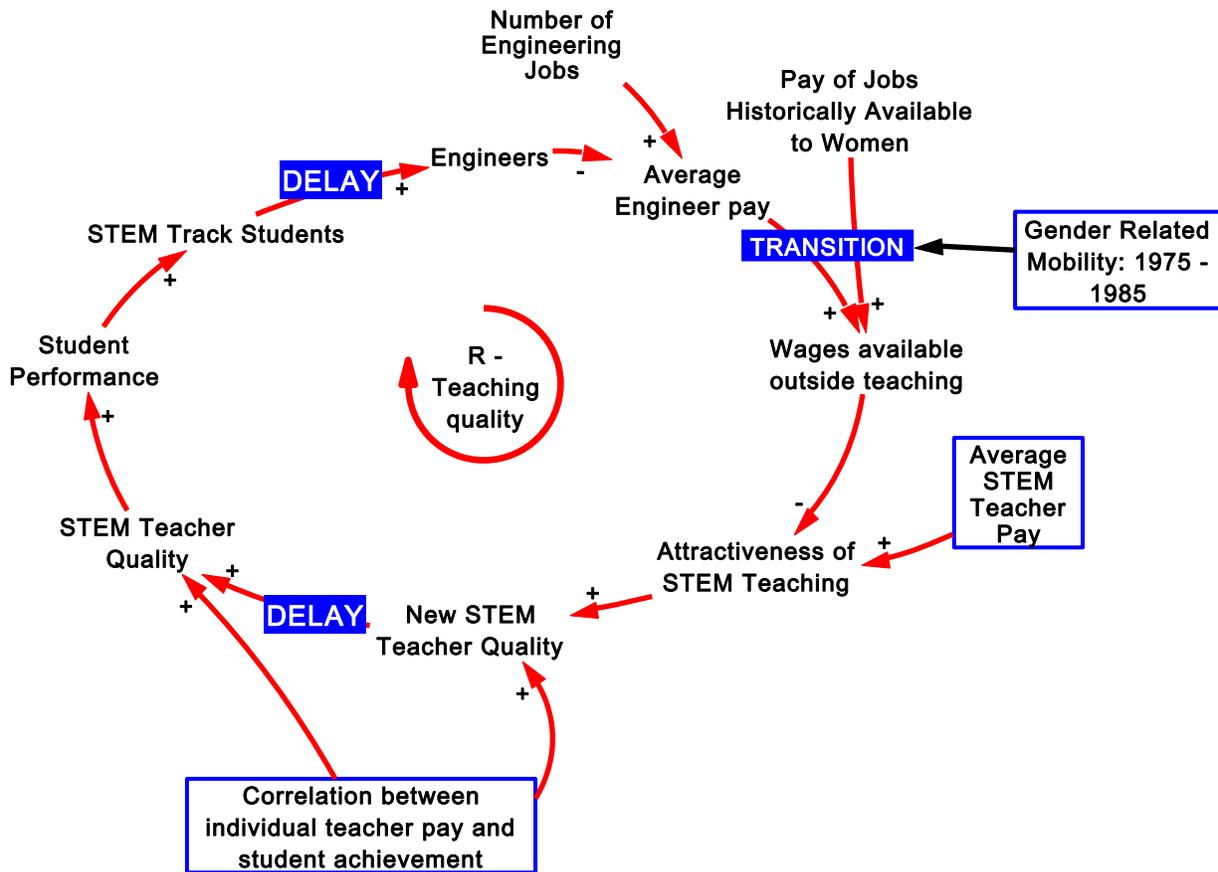


Figure 26: Teacher Quality Conceptual Reinforcing Loop with Quality Determinant Inputs

The figure above adds additional structure to test different historical scenarios. A transition governed by variables related to gender related mobility is set to occur between the years 1975 and 1985. These years were chosen somewhat arbitrarily because they correspond with the years of rapid growth of women earning degrees in engineering (shown previously.) Prior to these years, the attractiveness of teaching was determined by the pay of teachers relative to what women could earn in professions historically accessible to them. Because these wages were less than engineering wages, teaching jobs would be seen as relatively more attractive. By 1985, all potential teachers judge the attractiveness of STEM teaching

jobs relative to industry pay. Average STEM teacher pay is left as an exogenous variable so that it can be manipulated during policy testing. Another concept introduced in this model is a variable representing the level of correlation between individual teacher pay and student achievement. This variable representing the impact of the incentive structure governing how individual teachers are rewarded impacts the effectiveness of average salary increases on average teacher quality. A more positive correlation between individual teacher pay and student achievement will positively affect both recruitment effectiveness and the turnover rates of high-quality teachers.

2.8 Final Conceptual Model: Invisible Hand, STEM Gauntlet, and Teacher Quality Combined

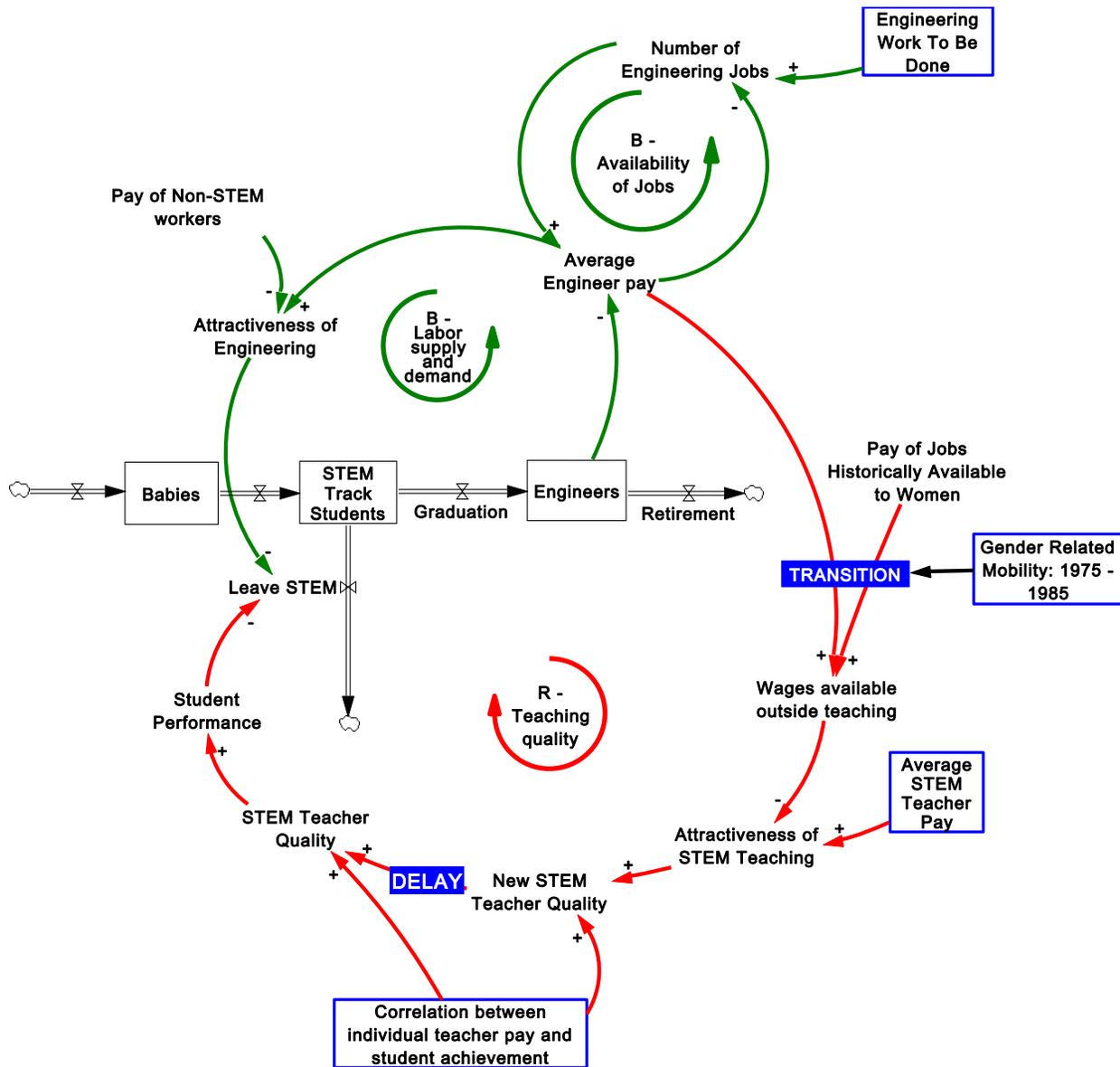


Figure 27: Invisible Hand, STEM Gauntlet, Teacher Quality Conceptual Structure Combined

This model is now integrated into the full conceptual model that has been developed over the course of the thesis. The ‘invisible hand’ and ‘teacher quality’ loops intersect at the point where a child either continues in STEM education or falls out of the pipeline. As stated earlier, the model assumes that the probability that a child continues on the STEM pipeline is a function of both ability and intent. After

years of delay, both the loops are influenced by the salaries earned by the professionals that made it through the gauntlet whose behavior they both governed.

The final conceptual model that has been created is a synthesis of all the literature presented up until this point. It is a combination of all previous pieces of structure that were built up incrementally. Model conceptualization was a very valuable method for organizing knowledge about the static relationships inherent in the system in a logical and consistent way. However, what is far from obvious at this point is how this system will behave dynamically through time. At this point, human understanding must be set aside because its limitations have been reached. While humans can build a model of the *form* of this system its *function* can only be understood by handing control over to the computer. From here on out, graphs of computer generated simulation runs will be presented to show how this largely self-contained system evolves internally based only on the structure and relationships that have already been specified. Some results will be straightforward. Others may be surprising.

This section ends with the story that the model tells: Employers have to compete with each other to get scarce talent. They respond to mismatches in the supply of STEM workers by raising or lowering their employment offers. If they can't find enough people, they are willing to pay more to get them. If there are a lot of people on the market, they negotiate harder. It's impossible for these wages to rise too far however because employers with STEM demands are only willing to pay so much before they become unprofitable. If that becomes the case, they don't open as many job requisitions. Wages never fall far quickly either because as the wages fall, employers open up new jobs as it becomes easier to be profitable. The fluctuation in wages influences how attractive STEM careers are perceived to be by society. Students in school and their parents respond to this perceived attractiveness by placing a higher or lower value on STEM education. This influences their tendency to study and stay in courses that will allow them to stay on track to eventually have a STEM career themselves. Meanwhile, these students are not learning in a vacuum. They go to school every day and are influenced by the abilities and interests of their teachers. Those who are lucky enough to have a succession of inspiring and knowledgeable STEM teacher and who are also encouraged outside the classroom are more likely to continue through the gauntlet because they perceive themselves to be good at it. Many more have a shaky handle on the material, some because of variations in individual ability, but more because some previously uninspiring or unknowledgeable teachers convinced them that STEM was either "boring" or "too hard." These students become more likely to focus in other areas and neglect their math studies. In later years, some are likely to say things like: "I'm just not good at math." Others will say things like "I'm more of an artistic person. I like humanities." While this may be true for some, for others it will simply be after-the-fact rationalization. They may use these rationalizations to drop down to easier math courses and only take the minimum STEM requirements to graduate from high-school. Meanwhile, students graduate from college every year to begin jobs in the workforce. Many have studied business, psychology, history, English. Some of them go into the work world and get entry level jobs that may be interesting or may be dead-end. They get paid around \$30,000 or \$45,000 to start. Some of these people choose to go into teaching. Meanwhile, a few of their friends leave school with degrees in computer science or engineering. These students are offered \$65,000 or \$75,000. Except for some saints who choose to enter "Teach for America" for two years before beginning their "real career" three years later, most of these students take lucrative offers and never look back. Not enough of these technically capable individuals with real project experience and exposure to technology end up in the schools to populate all the STEM classrooms. Some of the former history majors are pressed into teaching physics against their will

because they know algebra pretty well and got good grades in high school physics back in the day
This self contained world continues to spin through time as people become children, go to school, go to college, enter the workforce, and retire. No one really knows what's in store 10, 20, or 50 years down the road in this little world.

3 Simulating History and Projecting Forward

3.1 Assumptions and Initial Conditions

The notional model that was built up over Section 2 was actually built as a real software model that is shown in the appendices. This model simulates inside a software package called *Vensim*. *Vensim* takes model structure built by humans and projects forward in time to see what the behavior of the system will look like tomorrow based on what it sees today. In this model for instance, the model was set to begin in 1940. All initial conditions were set so the state of the system in 1940 is perfectly known. The model iteratively projects how the system will behave and builds up a picture over time to show how internal forces and pressures cause the system to change. The most interesting behavior is that which is *endogenous* or generated internally. Looking at graphs of simulation runs and seeing unexpected interactions or unintended consequences can provide great insight into the functioning of the system.

Simulations were run with the following set of characteristics:

- Simulations run from the year 1940 until the year 2040.
- No population growth is represented in the model. Birth rates are assumed to be constant.
- Dollars are constant. There is no inflation.
- Average wages are constant for everyone except for engineers and STEM teachers.
- Students at every grade level respond equally to the economic outlook of STEM work. This means, for instance, that if the current wages of engineers indicate that the pipeline exit fraction should be 20%, then both 20% of second graders and 20% of high-school sophomores leave the STEM pipeline during that year.
- Societal demand for STEM products and services are set to increase linearly between 1950 and 2040. This is intended to reflect the increasing importance of technology in our economic life.
- In some simulations women are liberated. They are allowed to enter the workforce starting with a transition period that lasts from 1975 to 1985. In others, the labor market for STEM teachers and STEM workers remain segregated.

Societal Demand for STEM Work

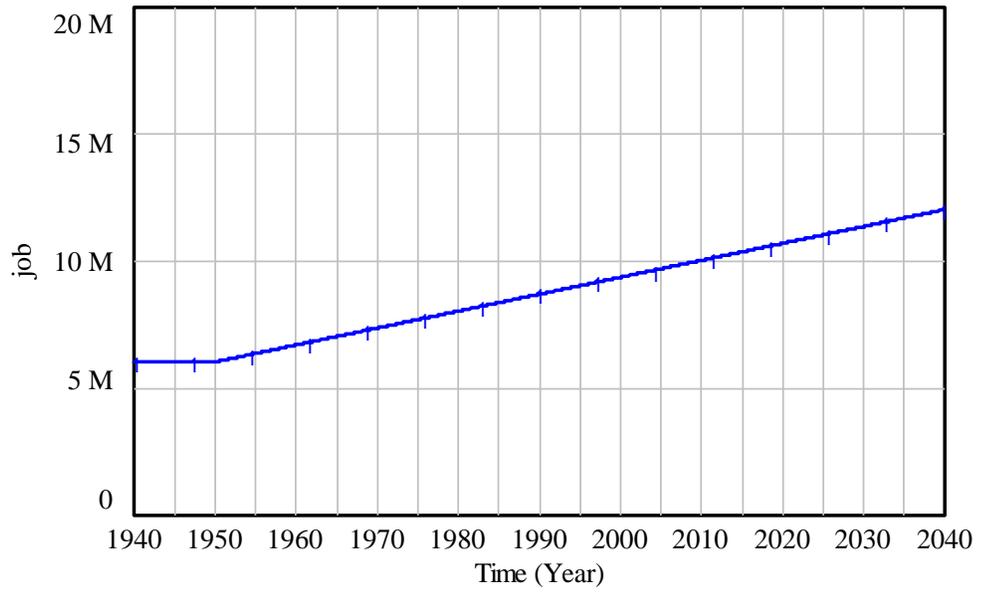


Figure 28: Societal Demand for STEM Work Increasing

3.2 Exogenous Non-linear Relationships

The conceptual model is complete with the exception that it inadequately describes the causal relationships between some variables. While most relationships between variables in the model are algebraic, five are specified using non-linear lookup tables in an attempt to make the system behave more realistically.

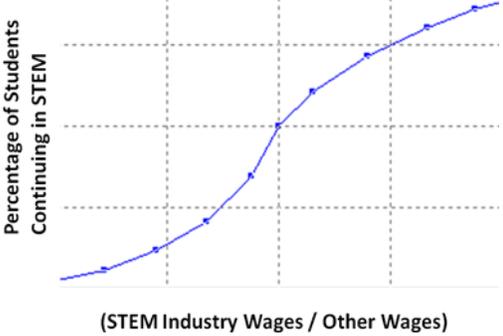
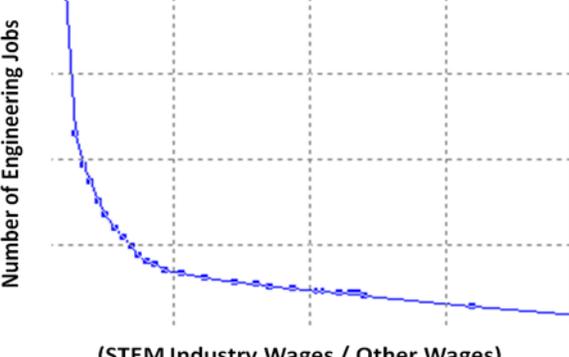
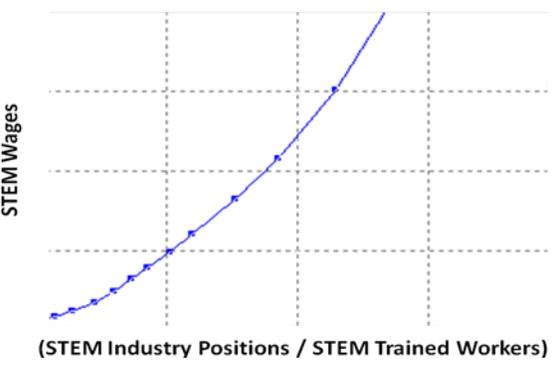
Variable name conceptual from model	Function determining value
<p>Figure 29: Engineering Attractiveness Function</p> <p>Attractiveness of Engineering: This variable determines the percentage of students who continue studying STEM in a given year based on the wages of STEM workers. A sigmoid-like lookup function is used to describe this relationship because increased pay will caused increased student motivation up to a point, but will then lead to diminishing returns.</p>	
<p>Figure 30: Engineering Jobs Function</p> <p>Number of Engineering Jobs: The number of jobs employers provide in the economy is a downward sloping demand curve. The demand for engineers is a function of their price. If wages go up, fewer jobs are available. If wages go down, more jobs are created. The current formulation is table that looks like a negative exponential function.</p>	
<p>Figure 31: Engineer Pay Function</p> <p>Average Engineer Pay: The pay of engineers is a function of the supply of engineers and the number of jobs currently available. This is currently formulated as a lookup function that looks like an upward sloping exponential function. A shortage of engineers will cause firms to bid up the price. A glut will cause wages to stagnate or fall relative to other jobs in the economy.</p>	

Figure 32: Student Performance Function

Student Performance: The fraction of students to continue on the STEM pipeline in a given year is a function of teacher quality. When quality is low, quality increases will have a large impact. This eventually leads to diminishing returns. There is an upper limit on the percentage of students that stay interested in STEM any year because many will naturally be attracted to other subjects.

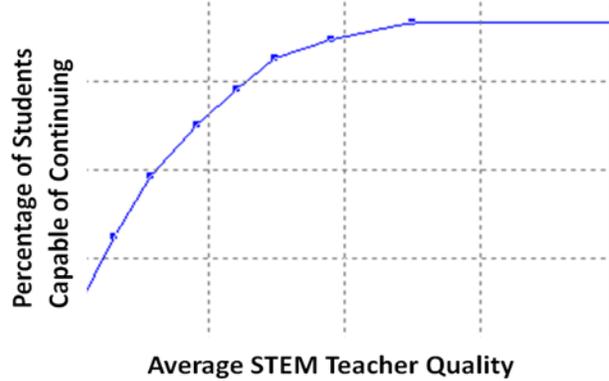
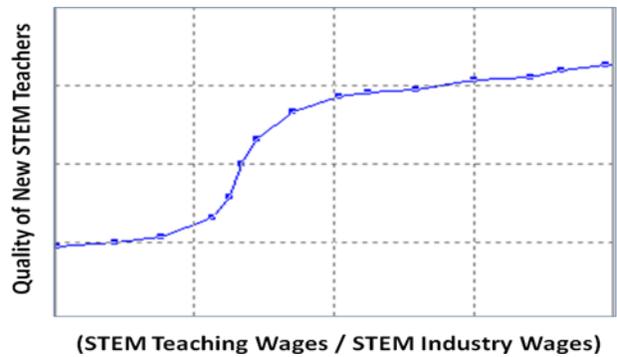


Figure 33: New STEM Teacher Quality Function

Quality of New STEM Teachers: The quality of new STEM teachers is a function of the opportunity cost associated with taking a teaching career. The system is most responsive to pay changes in regions where STEM industry and STEM teacher pay is close to equal. It is unresponsive at points that are much higher or much lower. This relationship has been described previously.



3.3 Baseline Case: Women Never Enter the Workforce

This set of simulation runs first is intended to demonstrate what would happen if the labor pools of STEM workers and STEM teachers had not been combined. Teacher quality continues to be quite high in these runs because although teachers are not paid as well as STEM workers, their pay is higher than most other jobs available to women. Because teacher quality remains high and constant, the only thing influencing student retention in STEM subjects is STEM industry wages.

Workers and Positions

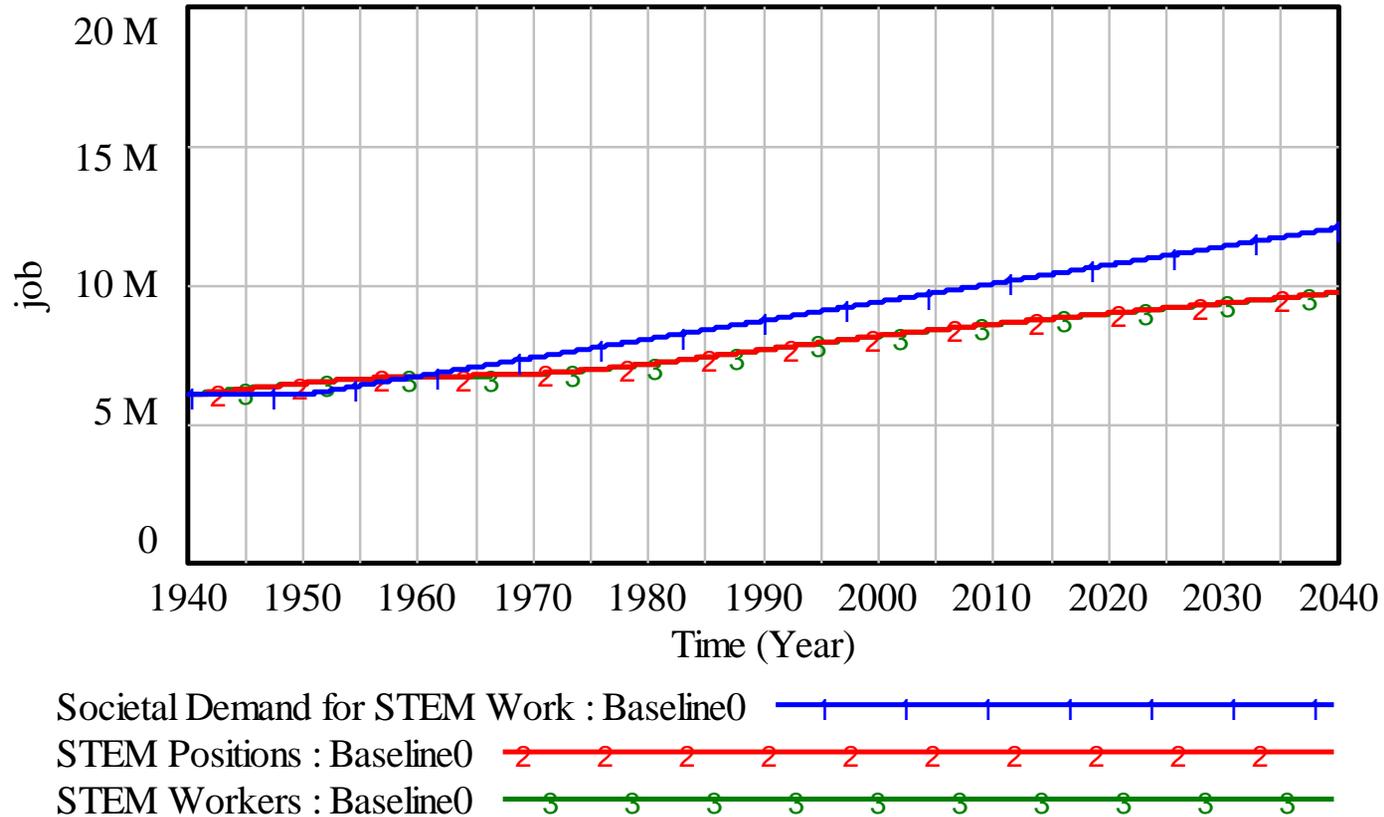


Figure 34: Full Model Baseline Workers

The “Societal Demand for STEM Work” rises has been set to rise starting in 1950. This causes employers to attempt to create “STEM Positions” to meet that demand. The number of “STEM Workers” also rise through time as more students graduate from college. Societal demand outpaces the economy’s ability to fill it to some extent because this demand is rising so rapidly and because of constraints in the educational system. The system is behaving rationally and moving in the correct direction however.

STEM Wages

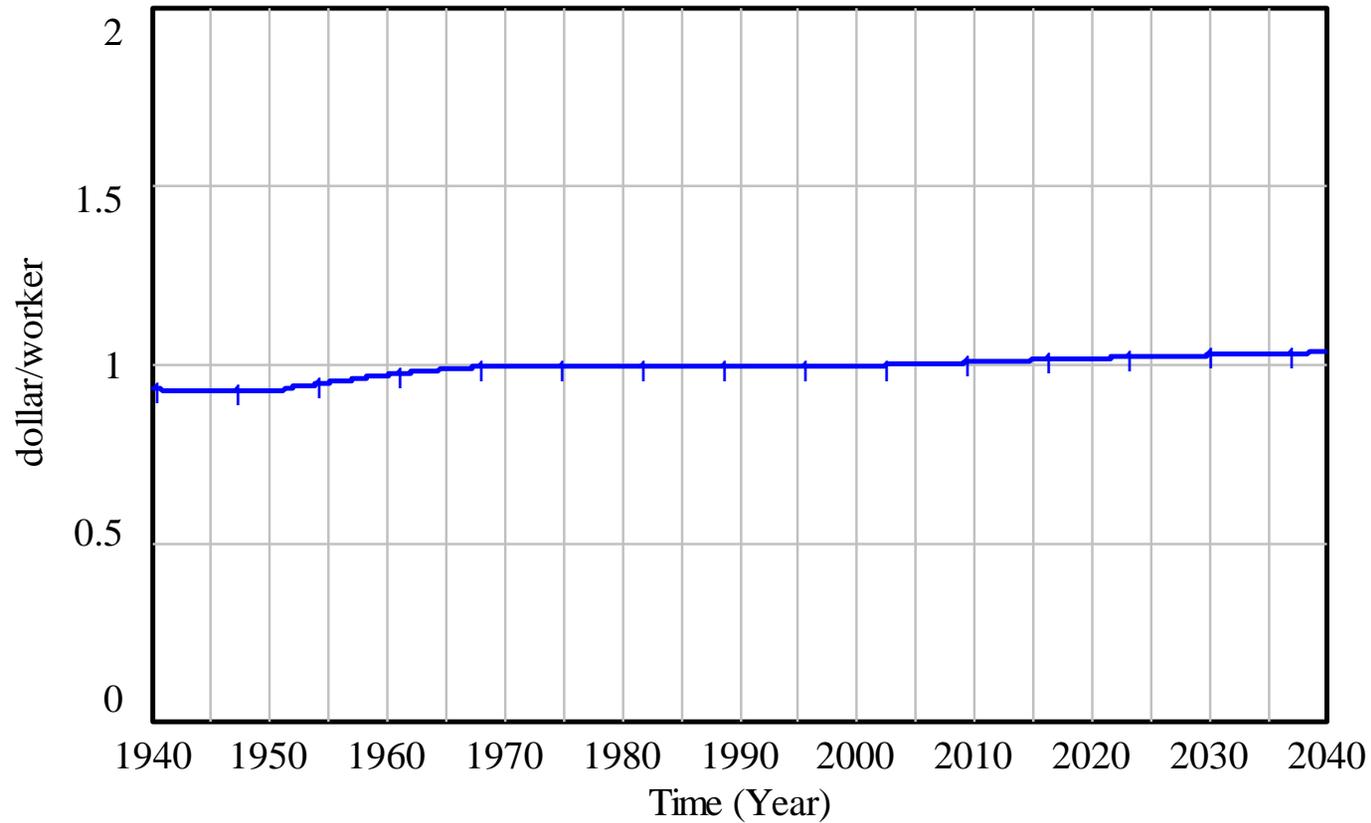


Figure 35: Full Model Baseline Wages

“STEM Wages” begin to rise in 1950 because employers facing shortages increase the amount they are willing to pay “STEM Workers.” As some societal demand continues to be unmet, STEM Wages continue to rise as employers bid up the cost of labor.

Staying Interested In STEM

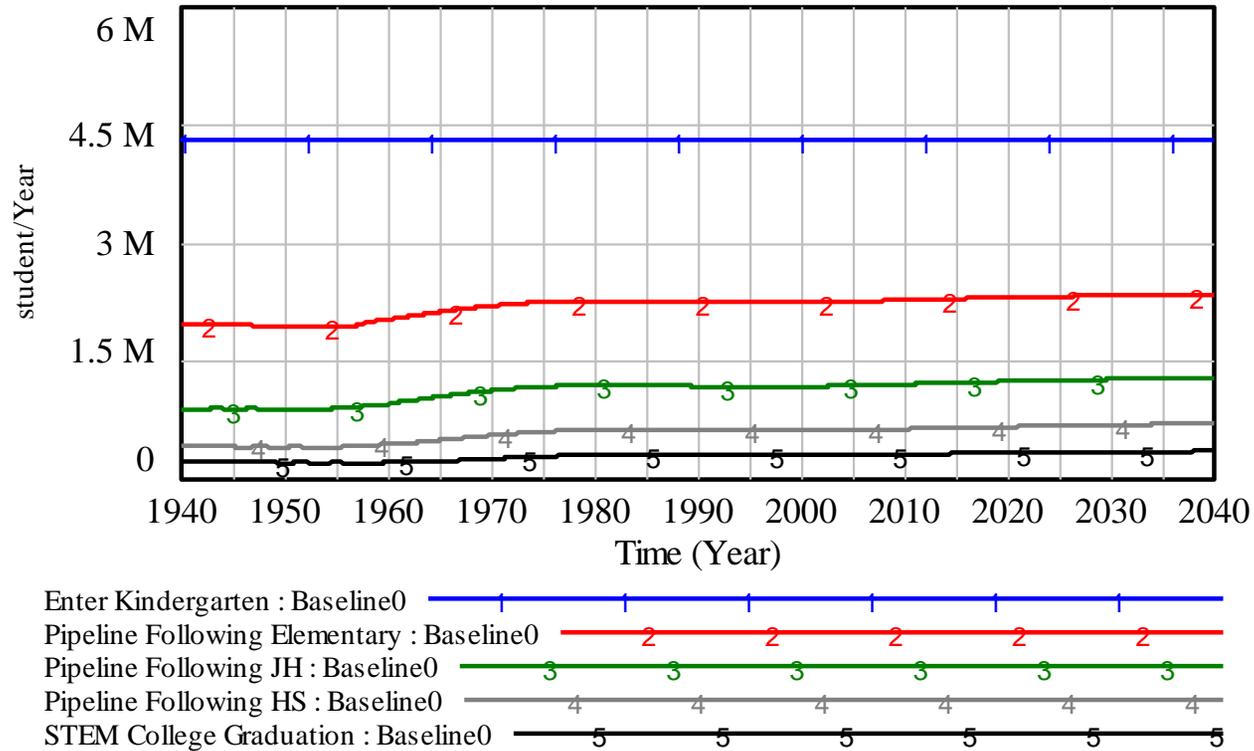


Figure 36: Full Model Baseline STEM Students

Because wages rise, more students at all levels (elementary, junior high, high school, and college) continue on the STEM track, either because they wish to maximize future economic return, or because social norms place increasing pressure to study STEM as a result of overall increased interest. Notice that the rise in the number of students graduating from college occurs well after the rise in elementary school students begins. This delay occurs because of the momentum in the system. Students are not allowed to reenter the pipeline after 1950 if they left it because of wage levels prior to that point. The number of college graduates does not fully adjust to new market conditions until many years later because of this constraint.

The previous system showed a reasonable, although constrained, response to increasing demand. The only structure active in this system was the STEM Gauntlet and the Supply & Demand loops. This is a very simple picture of the market operating to fix the problem.

One other thing to notice is about this simulation is the incredible constraints and delays built into the system. It takes ten years before the increase in market demand before any difference in college graduations into the STEM workforce occurs. The number of available jobs and workers never is able to fully catch up to the rapidly increasing societal demand for STEM goods and services.

3.4 Historical: Labor Markets Merge

This next model run is intended to depict a crude representation of what actually happened in the real-world system, and what will happen in the future if the current set of policies is maintained.

The following settings are in effect for this simulation:

- Liberalization of gender roles occurs and female STEM graduates are allowed to choose freely between teaching and industry professions after a transition period that happens over the course of 1975 to 1985.
- Pay of teachers remains constant over time. This pay is very good compared to jobs historically available to women, but much less than STEM workers make in industry.

Figure 38: Full Model Historical Teacher Wages

This value of “Teaching wages” is high relative to “Historical Womens Wages”, but low compared to “STEM Wages”. While STEM teacher pay remains flat, the wages that potential teachers compare against when choosing professions (“STEM Comparison Wages”) rise significantly. Prior to 1975 teaching is seen as highly attractive. During 1975 to 1985, women in STEM move into industry. During this transition period wage expectations grow. After 1985, STEM teacher wages are judged directly against the wages that women can earn in industry science and engineering jobs.

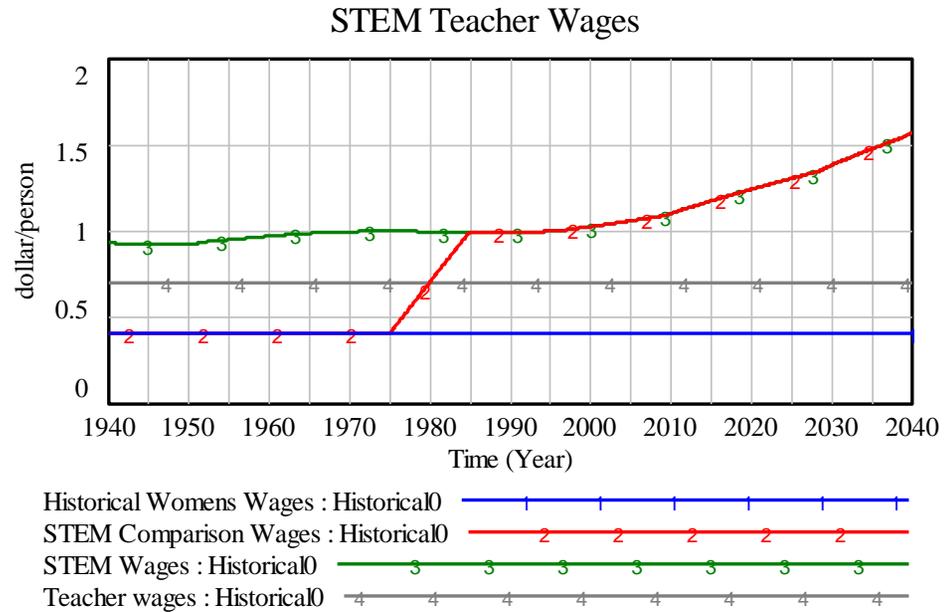
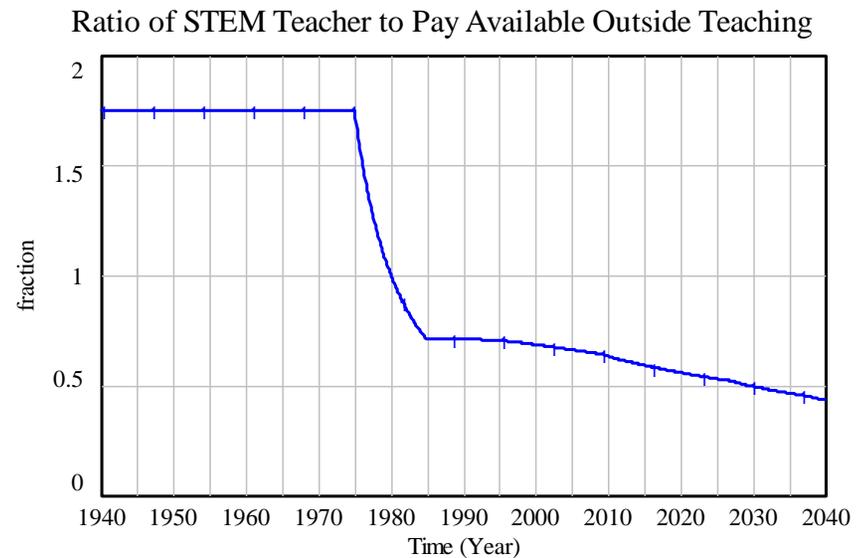


Figure 39: Full Model Baseline Teacher Wage Ratio

Because the opportunities available to women changed dramatically over the course of the simulation, the ratio of teacher wages to wages available elsewhere for women in STEM shrink dramatically. While female teachers are paid a premium relative to what they could get elsewhere previously, after 1985 they take a substantial penalty for choosing STEM teaching over industry work. This ratio continues to shrink further as STEM wages grow from 1985 onward.



Average Quality of STEM Educated Teachers

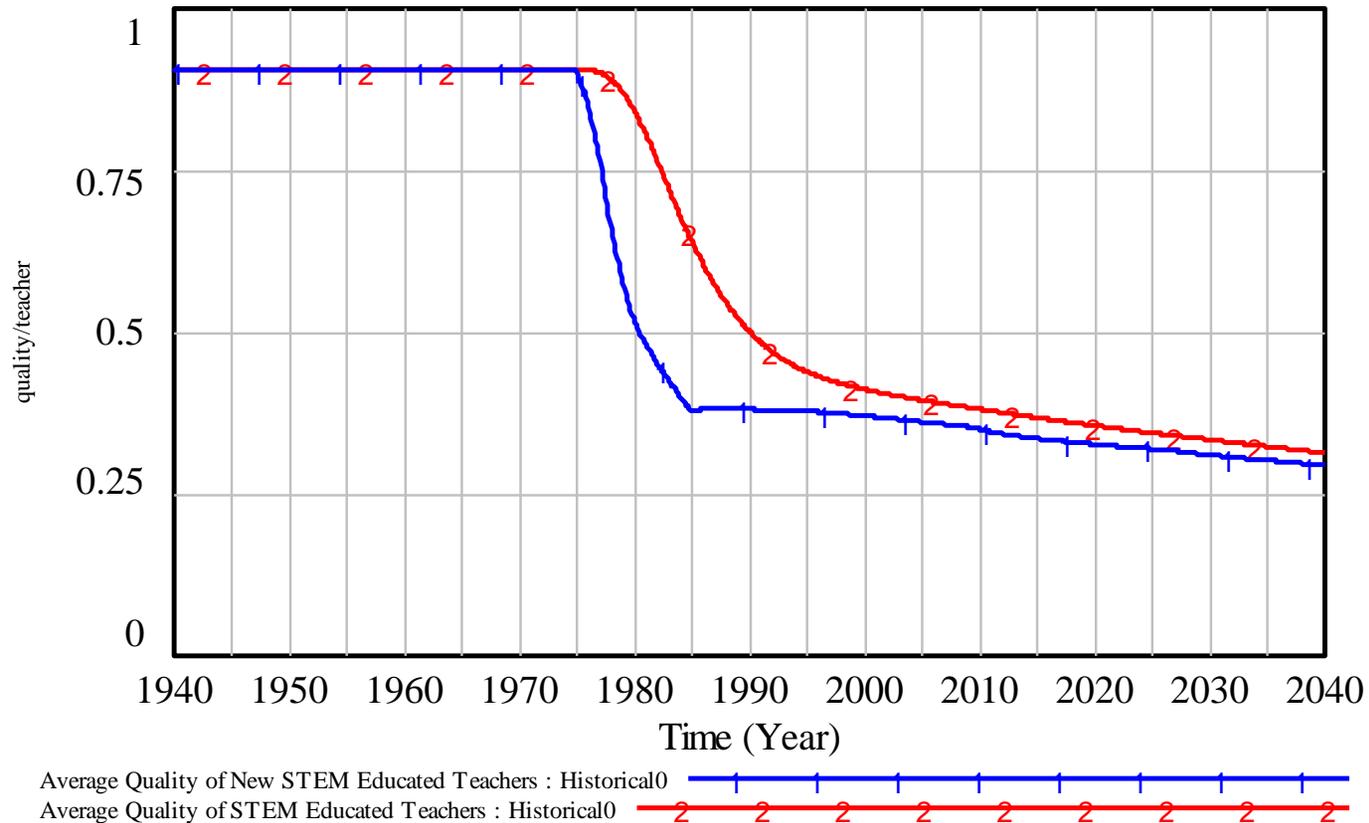


Figure 40: Full Model Historical Teacher Quality

Because teachers are paid a premium prior to 1975 and mobility was restricted, schools are able to draw from the best and brightest of fifty percent of the population. As other more lucrative opportunities open up however, the “Average Quality of New STEM Educated Teachers” drops. Over time, this causes a decline in the “Average Quality of STEM Educated Teachers” as new entrants come in and more senior teachers retire.

Figure 41: Full Model Historical Teacher Attrition

Because the teachers with very high quality have more lucrative opportunities open to them between 1975 and 1985, the “Fractional Teacher Attrition Rate” grows. As the quality of teachers drops, the opportunities available outside teaching for the average teacher also drop, causing attrition to slow again.

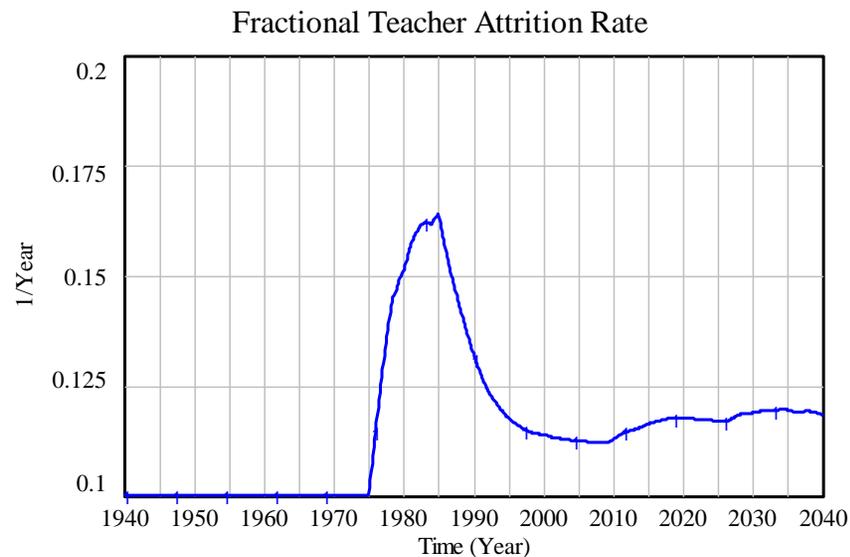
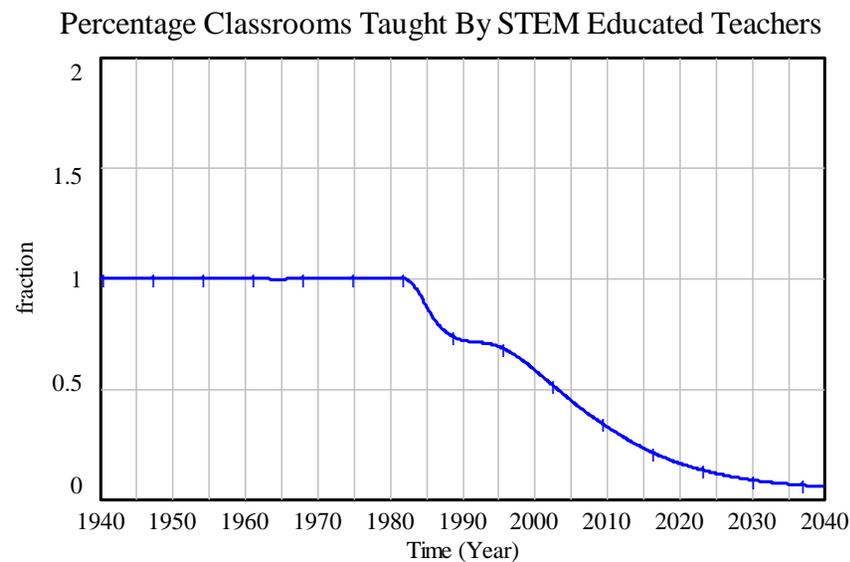


Figure 42: Full Model Historical Teacher Quantity

In addition to a quality decline in the average STEM educated teacher, a shortage of those teachers emerges. The “Percentage of Classrooms Taught by STEM Educated Teachers” drops. An increasing percentage of STEM classrooms must be taught by people untrained in STEM subjects.



STEM Classroom Quality

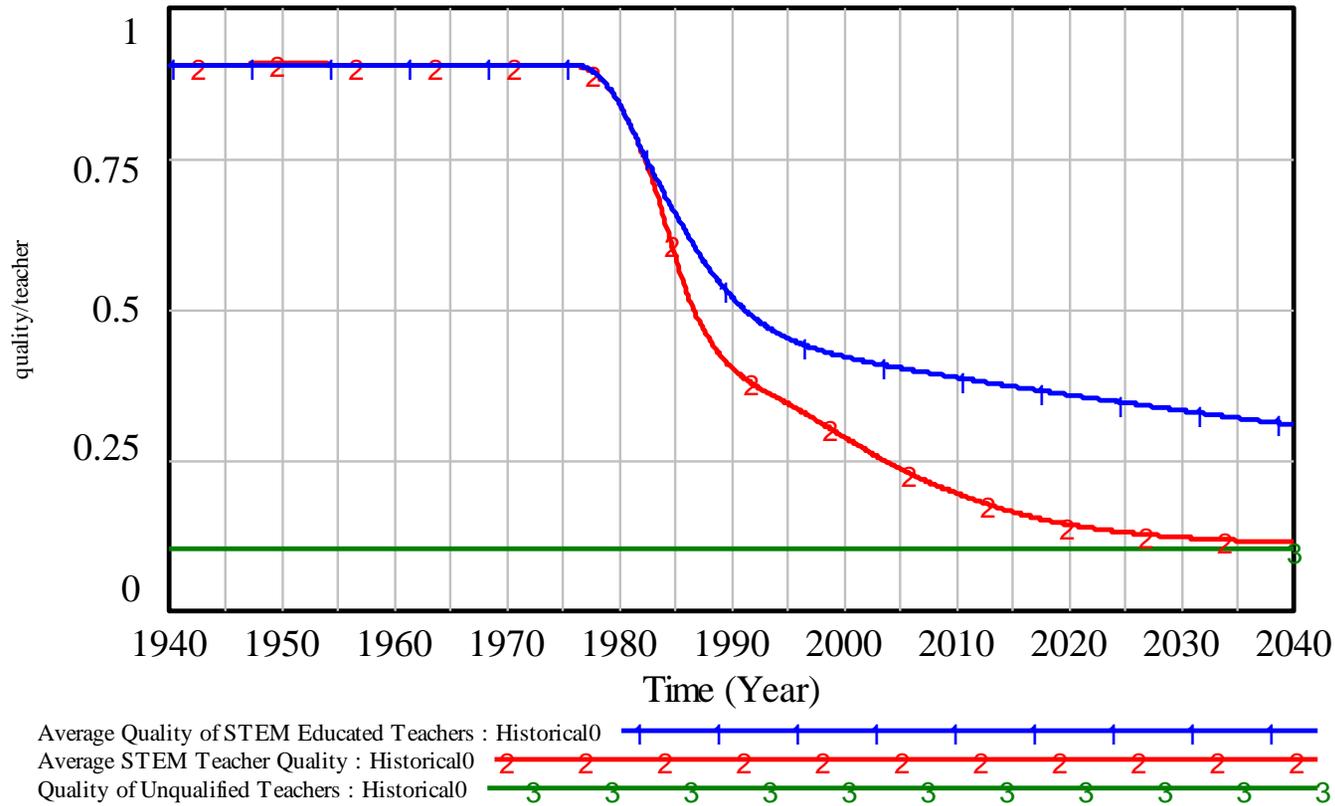


Figure 43: Full Model Historical Classroom Quality

The quality of the average classroom is influenced by two things. The first is the “Average Quality of STEM Educated Teachers.” The second determined by the fraction of classrooms taught by teachers with STEM training. Therefore, because of teacher shortages “Average STEM Teacher Quality” ends up much lower than “Average Quality of STEM Educated Teacher.” It is “Average STEM Teacher Quality” that students experience in the classroom.

Students That Continue in STEM Pipeline

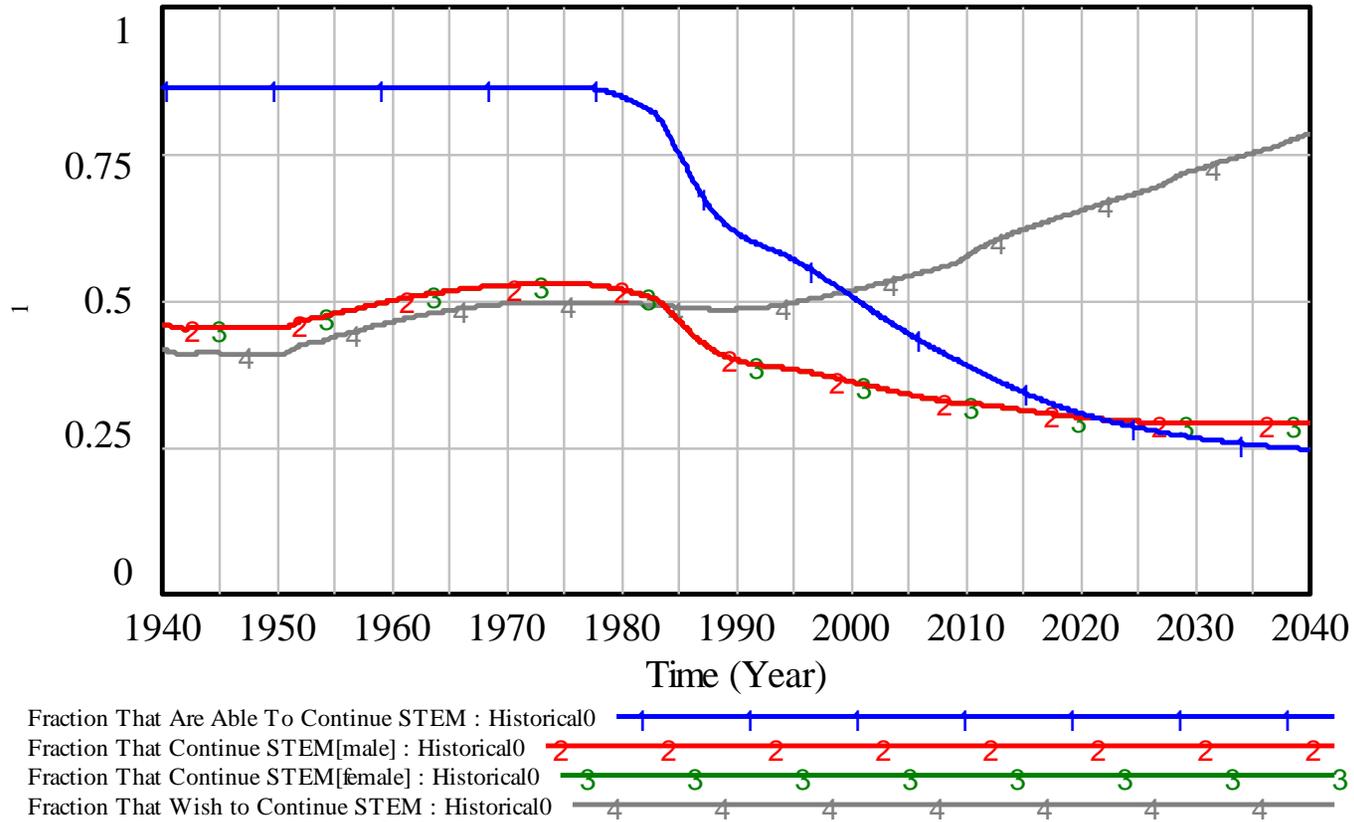


Figure 44: Full Model Historical Student Behavior

The fraction of students able to continue STEM drops as a result of the decrease in STEM classroom quality. More wish to continue on the pipeline as a result of increasing economic opportunity. The combined result of these two impacts make the “Fraction That Continue STEM” drop even though more students “Wish to Continue.” The combination of this increase in student desire, but decrease in quality education causes a decline in the number of students continuing on the pipeline at all levels. The peak of overall student ability to continue occurs in the mid-to-late 1970’s.

Staying Interested In STEM

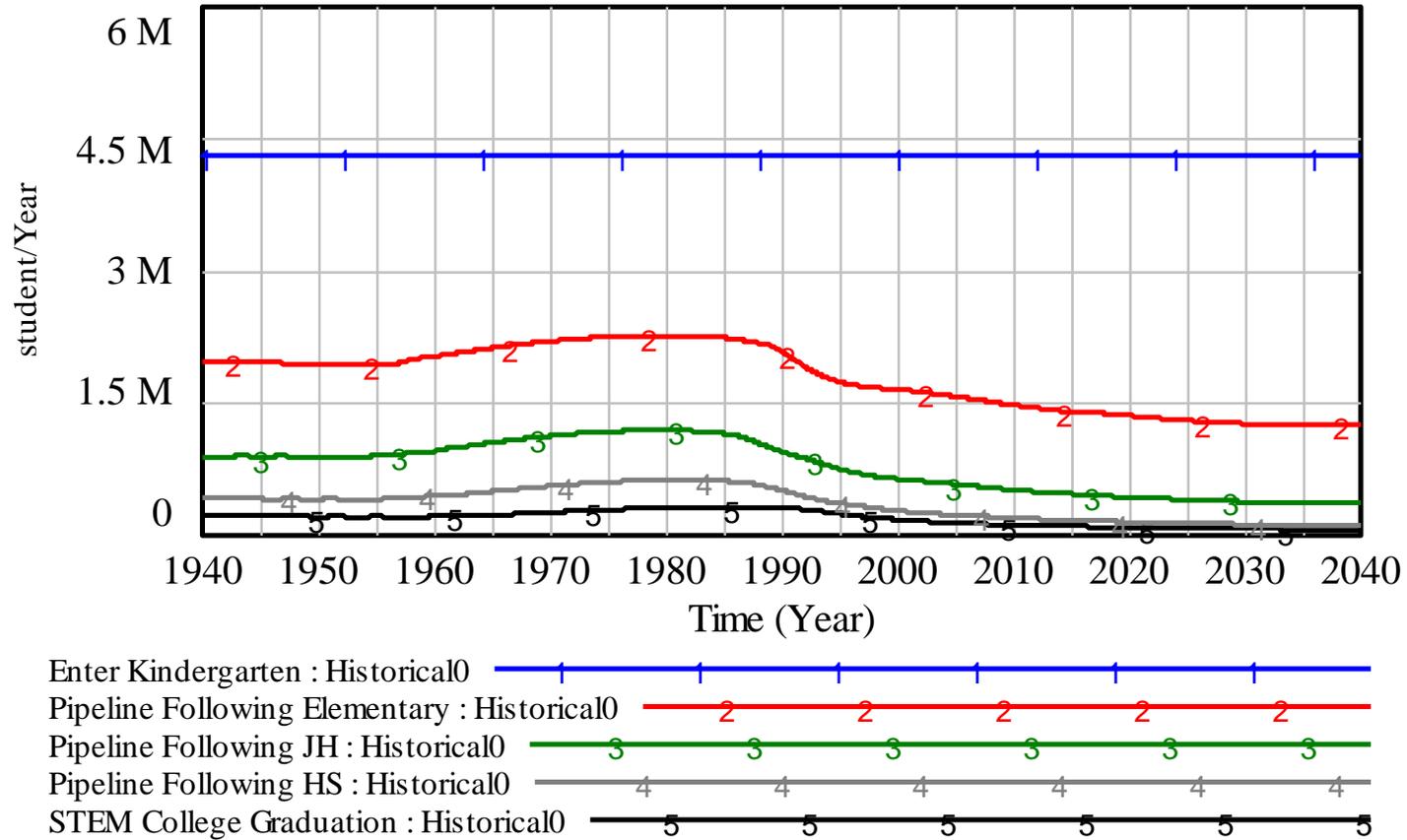


Figure 45: Full Model Historical STEM Students

As a result of a decline in the overall ability to continue, the number of students in the pipeline at all levels begins to drop after delays. Peaks in the number of students continuing on the pipeline at different grade levels occur at different times because of inertia in the system.

Figure 46: Full Model Historical Graduation

College graduations of STEM students (now shown to full scale) peak in the year 1986 and then drop significantly thereafter in this scenario. This graph qualitatively mimics the actual behavior shown in the real system. One thing to observe is that the number of graduations continues to fall through time with no increase in sight under this set of conditions. The fall trails off however because the system settles into a poor operating region of model behavior.

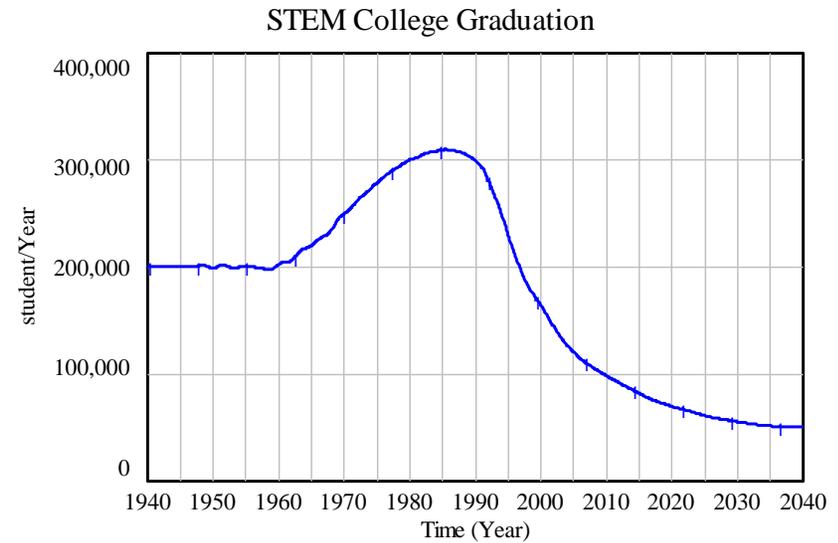


Figure 47: Full Model Historical Entering Workforce

Prior to gender related mobility “New STEM Teacher Hiring” remained flat because hires were able to match retirements. After gender related mobility however, increased turnover opened up many more positions. Many of the STEM graduates during In the 1980’s go into teaching to fill the demand left, but STEM teacher supply is unable to keep up with demand. These levels could not be sustained after the 1986 peak in STEM graduates because not enough STEM workers are available to either industry or to the schools. At this point the few remaining STEM workers tend to choose industry jobs because of substantially higher pay.

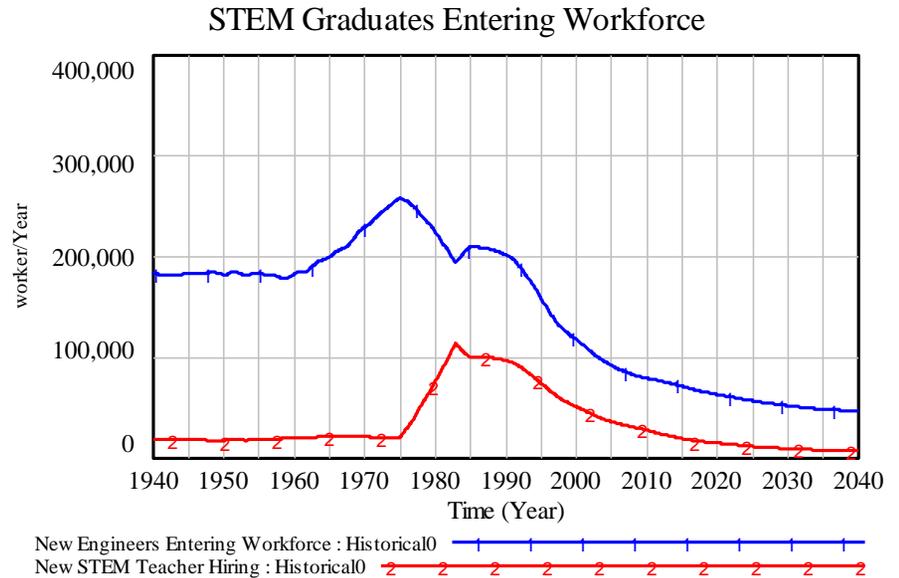


Figure 48: Full Model Historical Teacher Shortage

The number of STEM graduates going into teaching cannot keep pace with the “Desired Teacher Hires” so the shortfall of STEM qualified teachers continues to get worse.

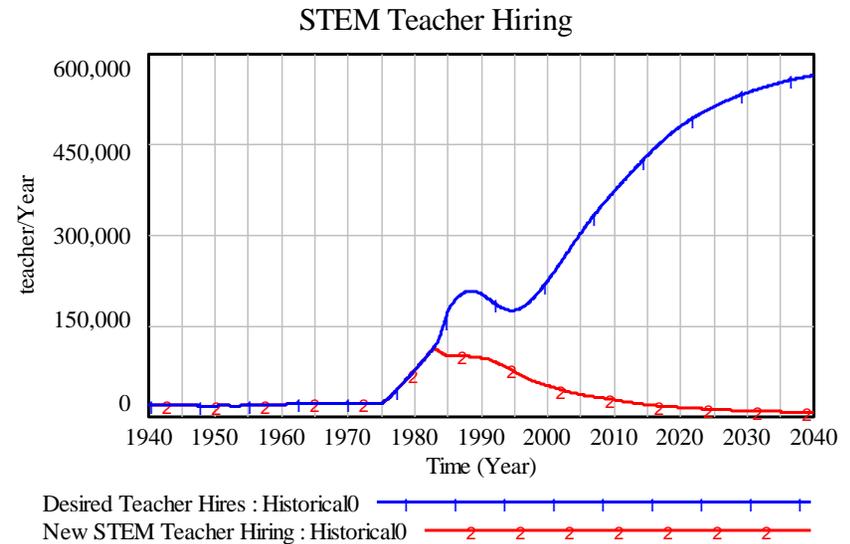
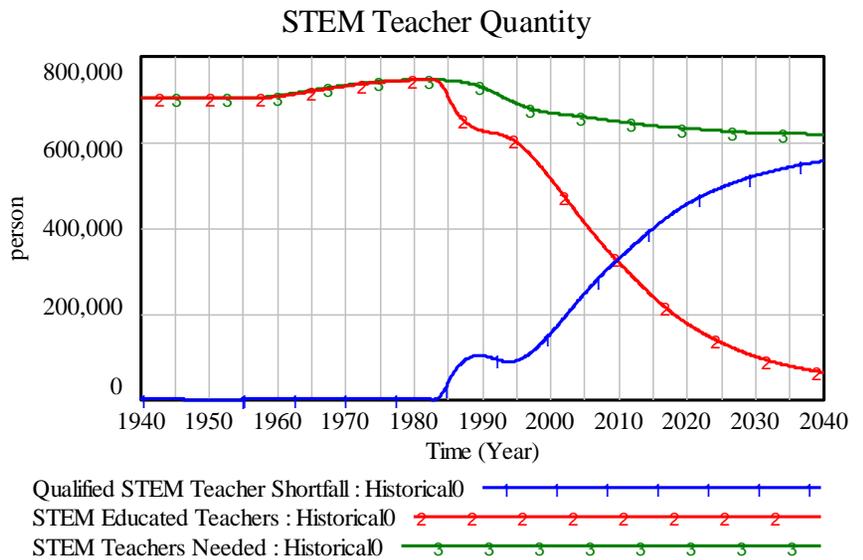


Figure 49: Full Model Historical Teacher Quantity

As a result of the “Qualified STEM Teacher Shortfall”, classrooms are taught by teachers without STEM credentials. Sadly, the demand for STEM teachers actually drops somewhat over time because fewer students take high-level math and science courses because more have already fallen off the pipeline in earlier years. By 2008 close to half of classrooms are taught by unqualified teachers. By 2040, 80 to 90% are.



STEM Teacher and Industry Wages

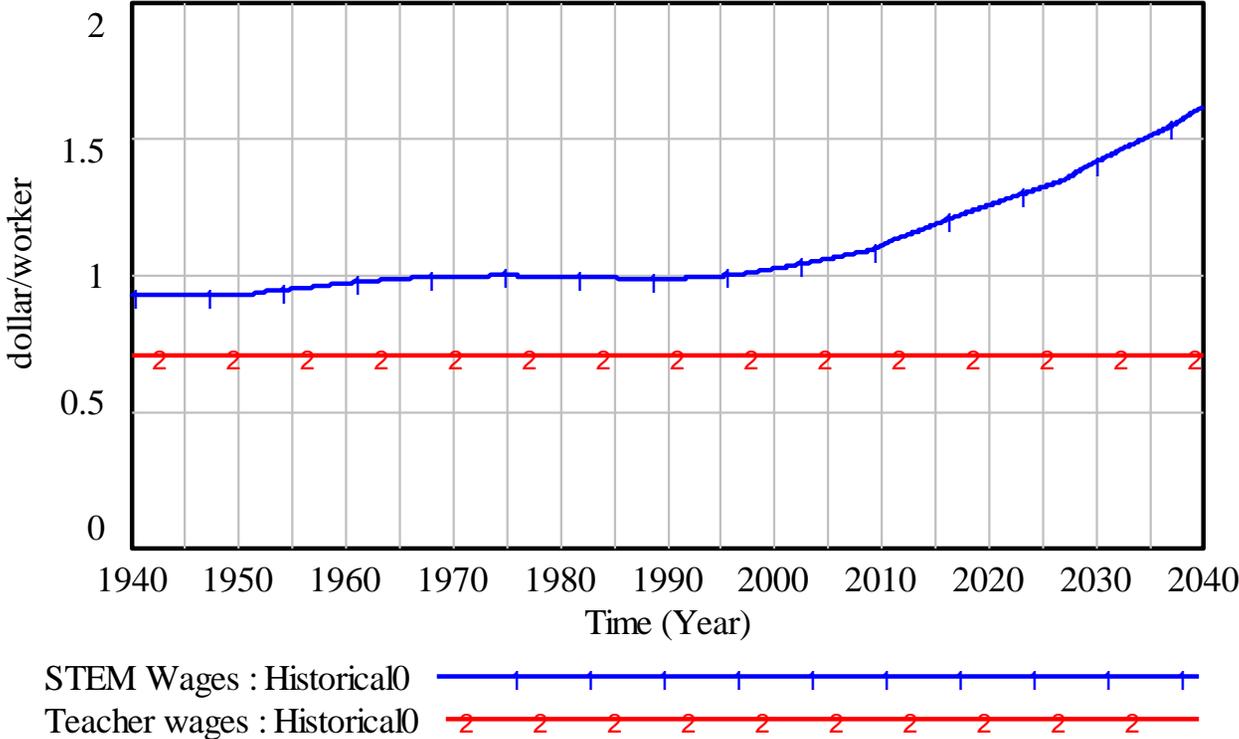


Figure 51: Full Model Historical Wages Diverge

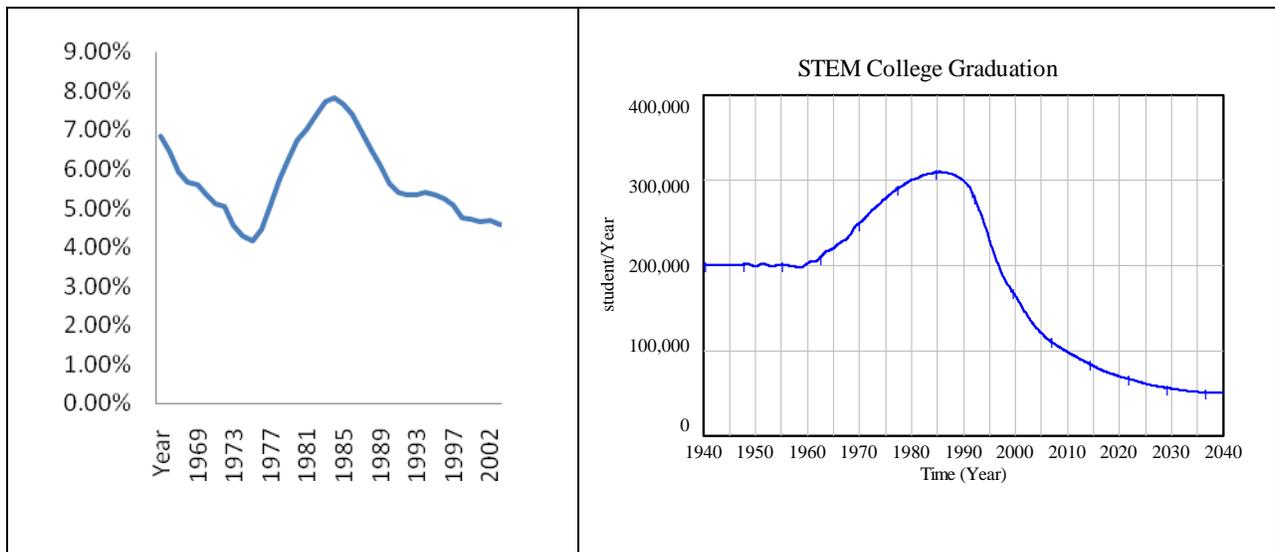
As a result of a decrease in the number of STEM college graduates and STEM workers, wages begin a dramatic rise in 1995 because industry bids up the price of scarce skills. The gap between teacher pay and industry pay widens further causing the quality of STEM education to further decline. This perverse nature of this positive feedback relationship causes the number of graduates in STEM fields to decline at the same time that STEM wages rise. The long-term impact of teacher pay constraints make rational short-term “invisible hand” responses of industry lead to perverse outcomes over the course of generations.

3.5 Insights from Historical Simulation and Future Projection

The model presented here is capable of producing behavior in which high pay in STEM fields directly causes future long-term labor shortages in those same fields. The dangerous loop we explored could be influential in any situation in which teachers earn less than practitioners and there is a scarcity of practitioners. The system might systematically under-produce exactly what the economy needs most in the long run. This would be especially pronounced in fields requiring knowledge with strong vertical dependencies (and therefore long lead-times and high-barriers to re-entry) such as mathematics. The system is perfectly rational in the short term - industry bids up the price of more valuable skills and draws people out of other places – including teaching. This economic signaling mechanism increases the short-term availability of practitioners, but could destroy the long term production capability for those skills, creating chronic shortages that are self-perpetuating after decades of delay.

Another notable feature in the model is the incredible inertia in the system. The impact of merging the labor force for STEM teachers and STEM workers took decades to play out. For instance:

- Women start to move into the workforce in 1975
- College STEM graduations peak in 1986
- STEM teacher shortages begin in 1987
- STEM wages begin to rise noticeably around 1995
- The number of STEM workers in the economy peaks around 2000
- Then the U.S. STEM industry then begins a downward spiral



The original problem statement asked why the number of engineers peaked in 1985 and then declined thereafter. This simulation has been able to successfully reproduce a peak in the number of graduating at the same time that wages stay strong or even grow. The simulation predicts that wages will continue

growing relative to other jobs in the economy and that the size of the U.S. STEM capable workforce will continue to decline.

While 1985 may have been somewhat significant in the short-term because it represented a ‘tech bust’ that occurred at that time, it is doubtful that the results of that bust would continue through today. What is more likely is that events in 1985 had no real significance in causing the long dramatic drop. Rather, increased demand for engineers during the early years of the Cold War, teacher unionization in the 1960’s, and the liberalization of gender roles in the 1970’s all helped to strengthen the power of the reinforcing loop and tip it in a negative direction. The impact these events had on engineering graduations would not be felt until decades later.

4 Simulating Alternative Futures

In addition to helping us understand both history and our current future, another use of a historical simulation is to generate a baseline from which alternative policies going forward can be tested. Even if the baseline values are not calibrated perfectly, the behavior of system response to policy changes relative to the historical run can give insight into which reforms will have the most impact. A number of simulations are presented in this section that assume ‘historical’ behavior until the year 2008 and switch to some other policy to test the impact of that reform.

4.1 Fixed Wage Increase of 10 Percent

The first policy tested is an across the board increase in STEM teacher wages of 10 percent. It should be noted that because simulations are in constant dollars, this persistent ten percent increase is in addition to a yearly inflation adjustment. If inflation is 3 percent then this simulation represents a 13 percent increase followed by three percent increases thereafter.

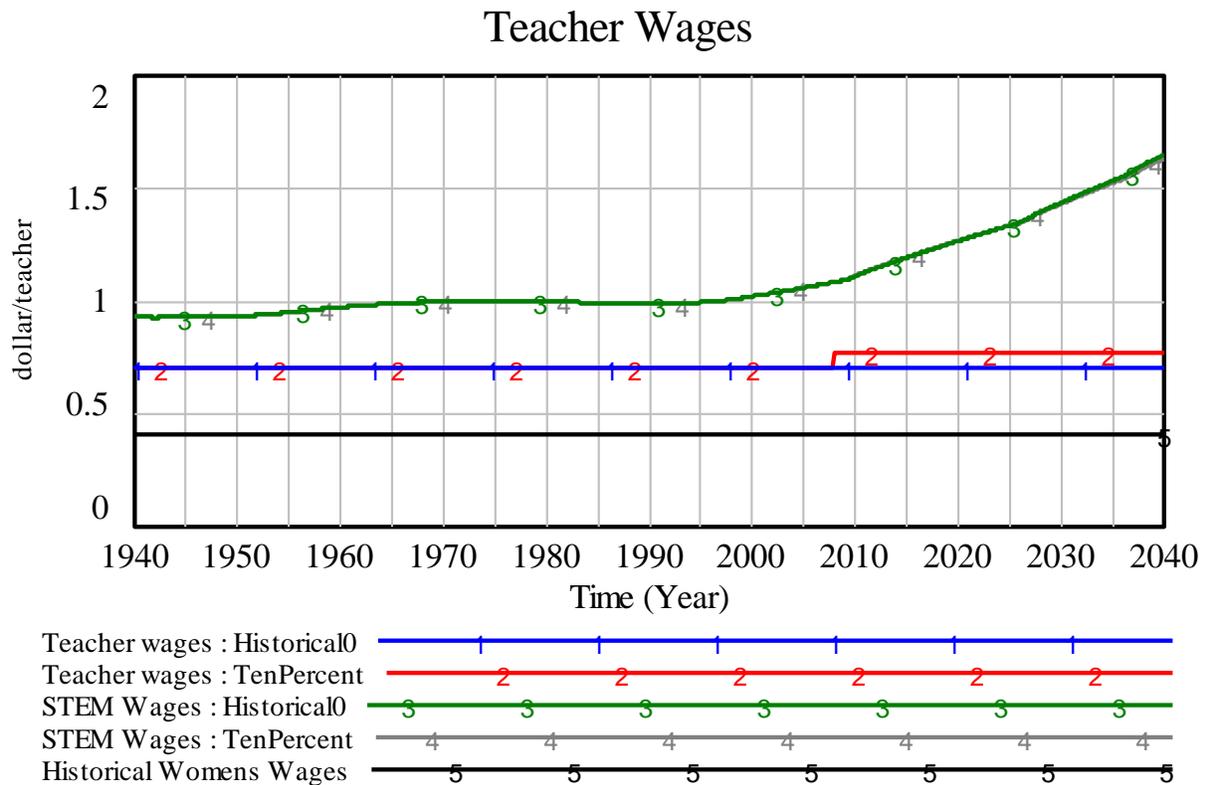


Figure 52: Policy Test Fixed Increase Teacher Wages

Average Quality of New STEM Educated Teachers

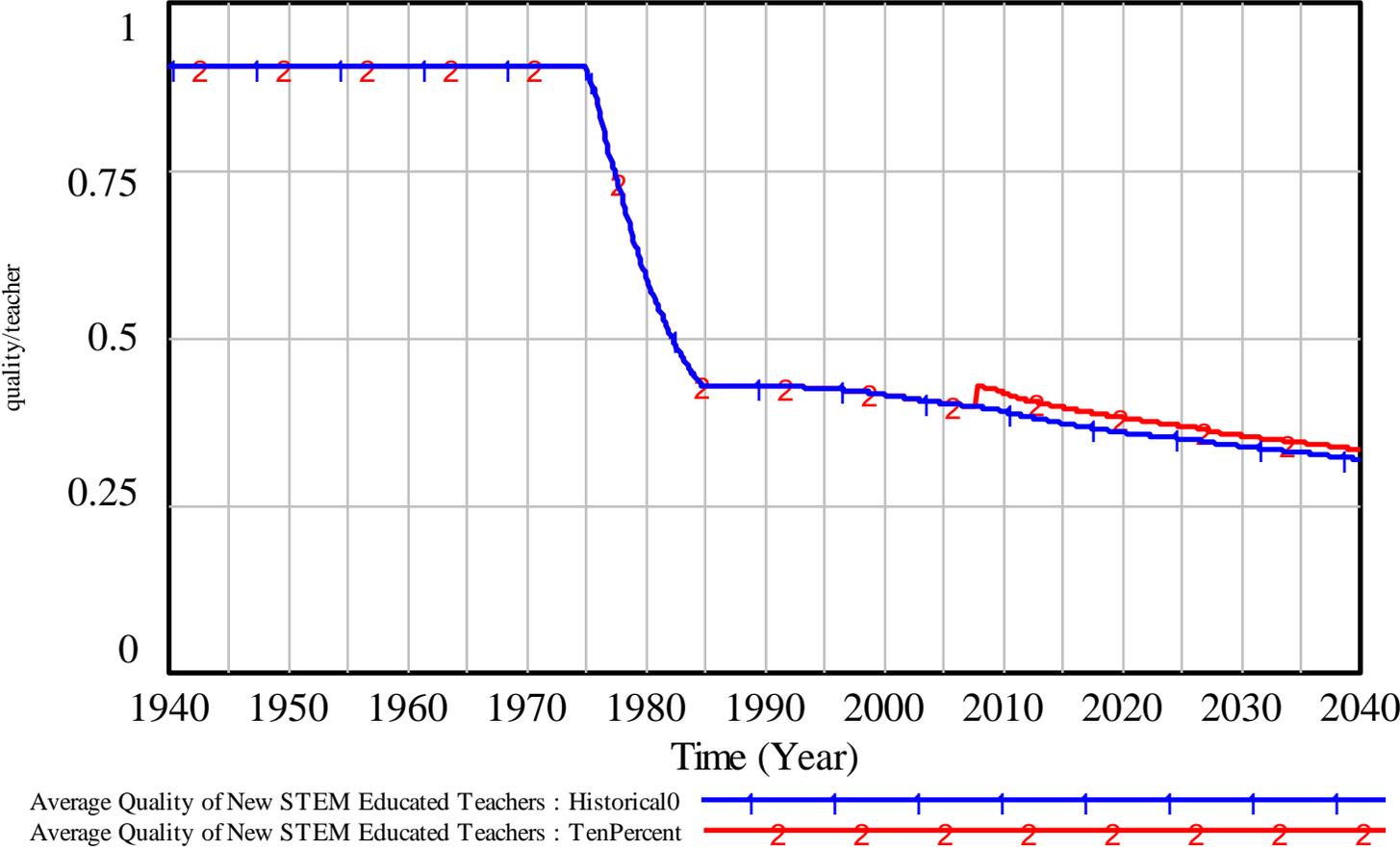


Figure 53: Policy Test Fixed Increase New Teacher Quality

While a ten percent increase seems fairly large to policymakers, it makes minimal impact on the ratio of STEM teacher wages to STEM industry wages because these wages are so far apart. Quality rises a little bit, but then continues to drop as STEM industry wages continue to rise.

Fractional Teacher Attrition Rate

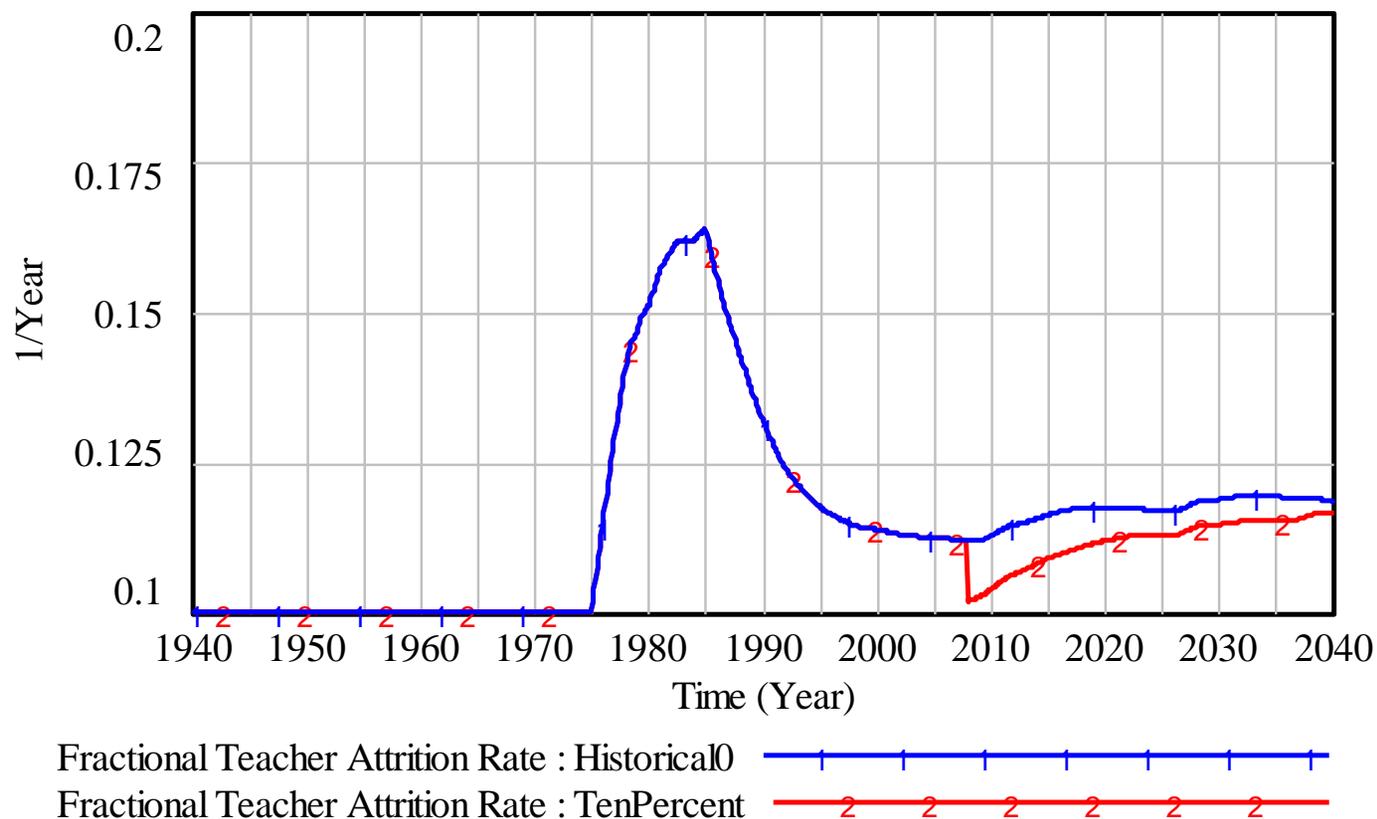


Figure 54: Policy Test Fixed Increase Teacher Attrition

While the impact of the wage increase has minimal impact on new teacher quality, it decreases attrition because teachers at the current average quality level are paid more than they expected to get when entering the profession. This decrease in attrition means that fewer of the new teachers with slightly higher quality are actually hired because there are fewer slots to fill.

Percentage Classrooms Taught By Qualified Teachers

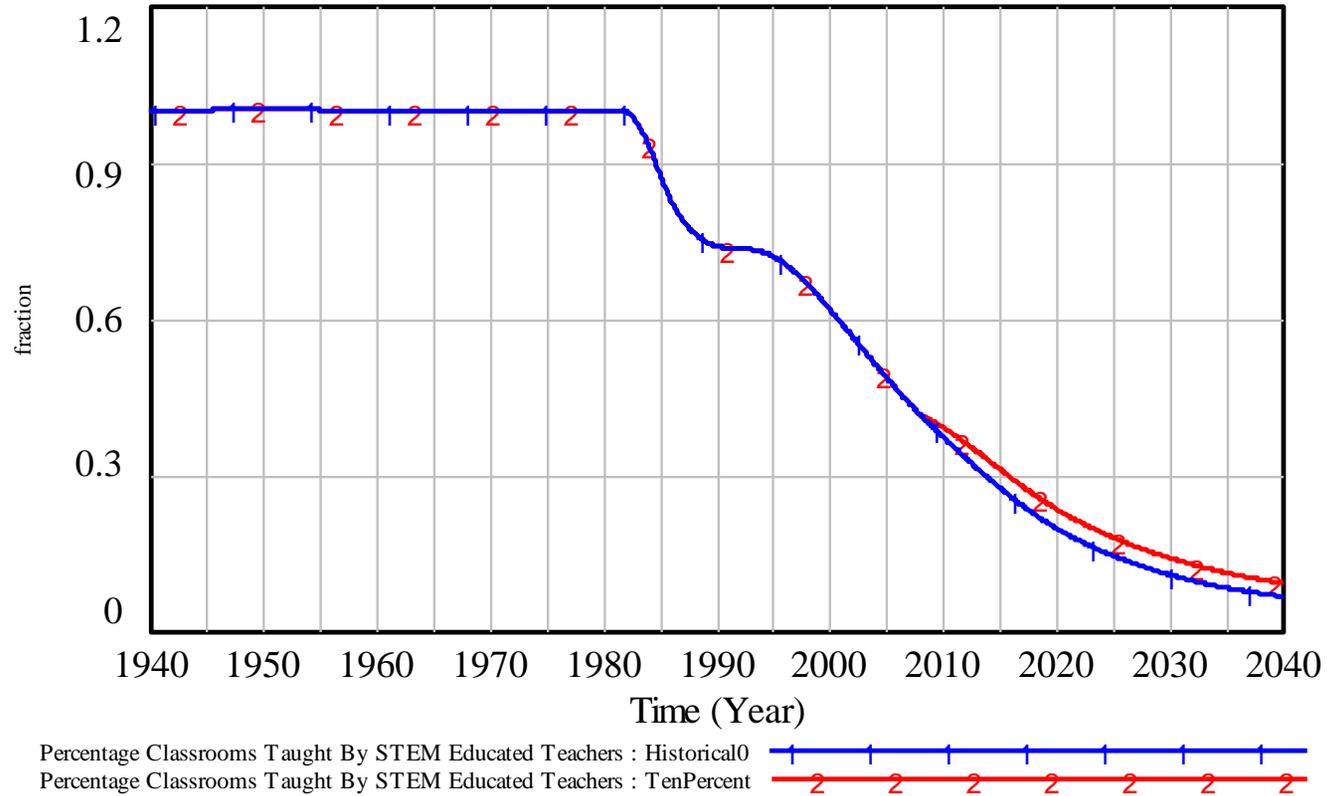


Figure 55: Policy Test Fixed Increase Teacher Quantity

An insignificant increase in the percentage of classrooms taught by STEM trained teachers occurs.

STEM College Graduation

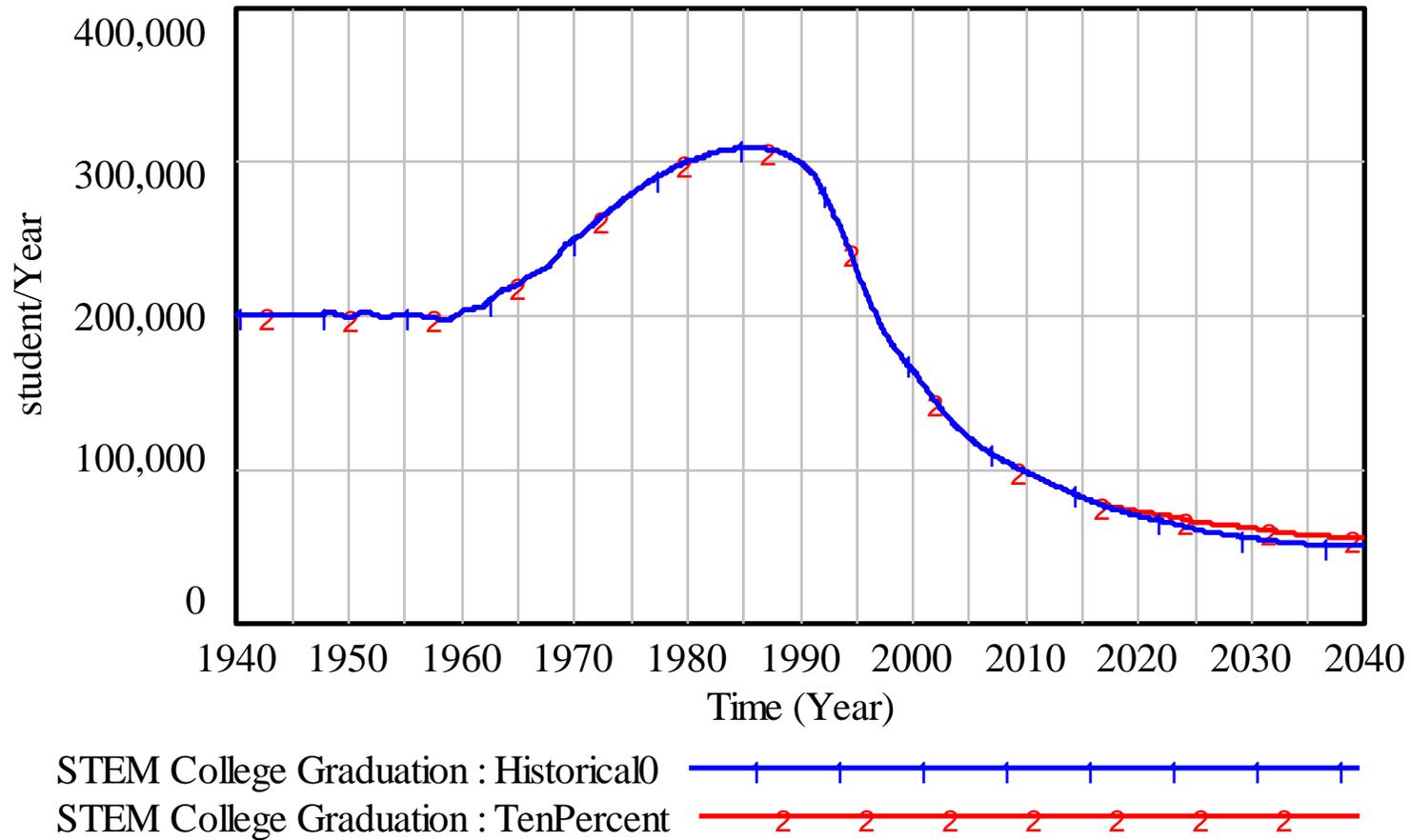


Figure 57: Policy Test Fixed Increase College Graduations

This reform fails to impact American capabilities in STEM.

4.2 Different Fixed Wage Increases

If a ten percent wage increase will have no impact on the system, other fixed wage increases amounts above ten percent still may. In this section a variety of fixed wage increases are tested.

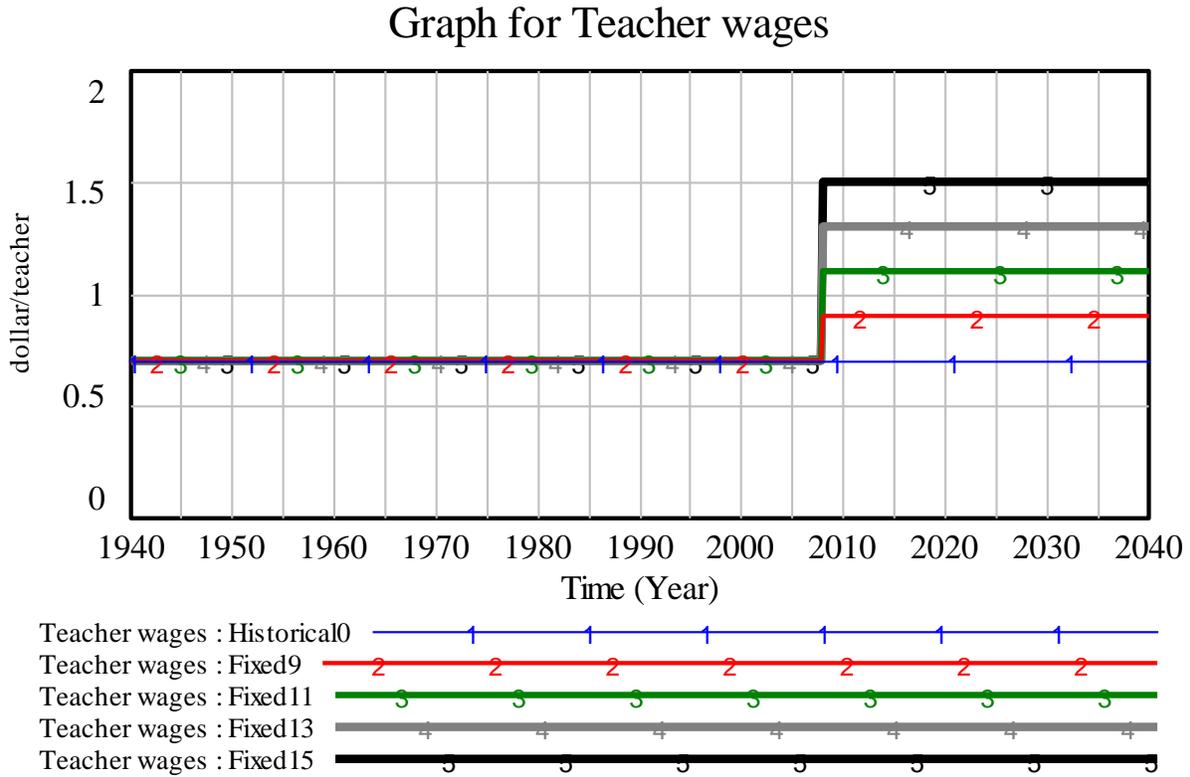


Figure 58: Policy Test Multiple Fixed Increases

Wage level in the historical scenario was set at 0.7. Other values tested after 2008 now include 0.9, 1.1, 1.3, and 1.5. In the historical scenario, STEM industry wages had grown to slightly above 1.0 by 2008 in the historical scenario. Therefore, most wage increases tested here make teacher wages rise above those of STEM workers today.

STEM Wages

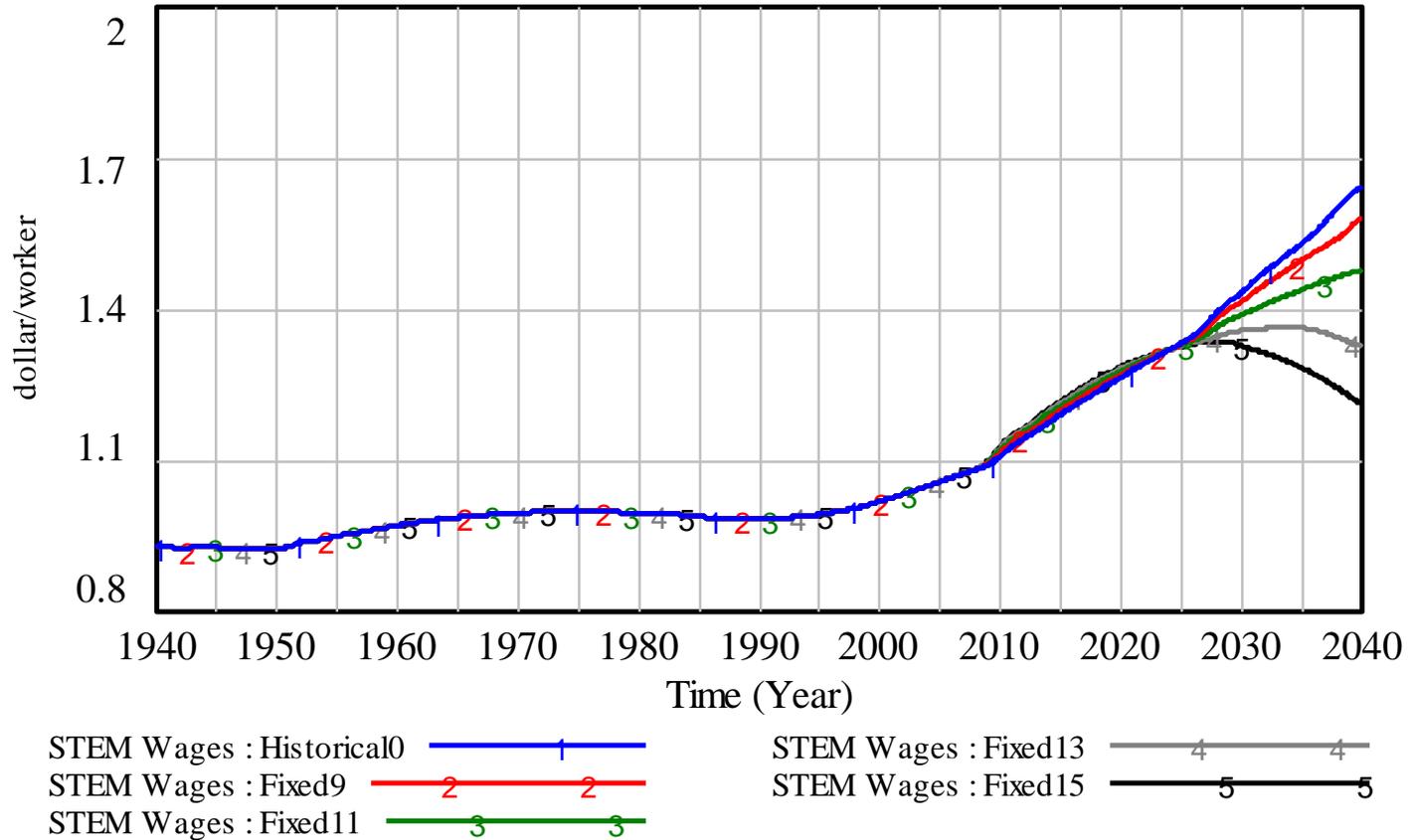


Figure 59: Multiple Fixed Increases STEM Wages

“STEM Wages” continue to rise in response to the growing shortage until 2025. In fact, they rise faster than the historical case because more STEM workers are in teaching rather than industry. In 2025, “STEM Wages” exhibit what is called “tipping point.” Low wage increases have virtually no impact while larger wage increases cause enormous impact by reversing the downward spiral, thus causing a fundamental change in the dynamic behavior of the system. Fixed teacher wages increases can be made high enough to cause positive feedback loop to ‘tip’ into a more virtuous behavior.

Average Quality of New STEM Educated Teachers

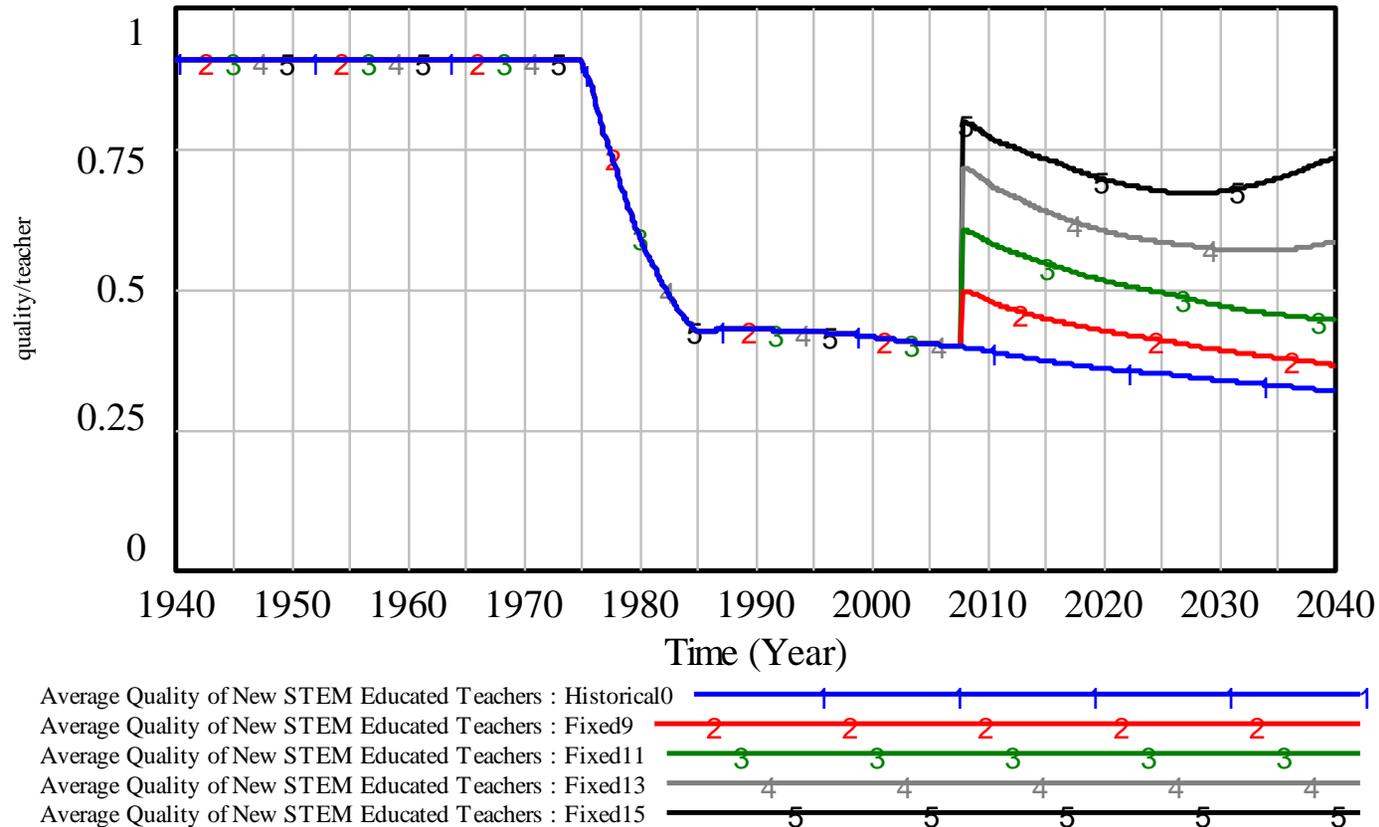


Figure 60: Multiple Fixed Increases Teacher Quality

The average quality of new teachers rises significantly in response to the wage increase. As STEM industry wages continue to rise however, the quality again begins to fall. Under some scenarios (when wages in STEM industry drop twenty years later) quality begins to rise again in 2028.

Fractional Teacher Attrition Rate

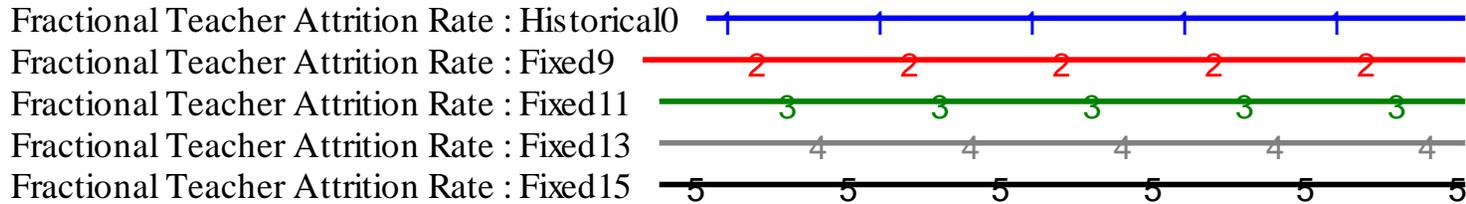
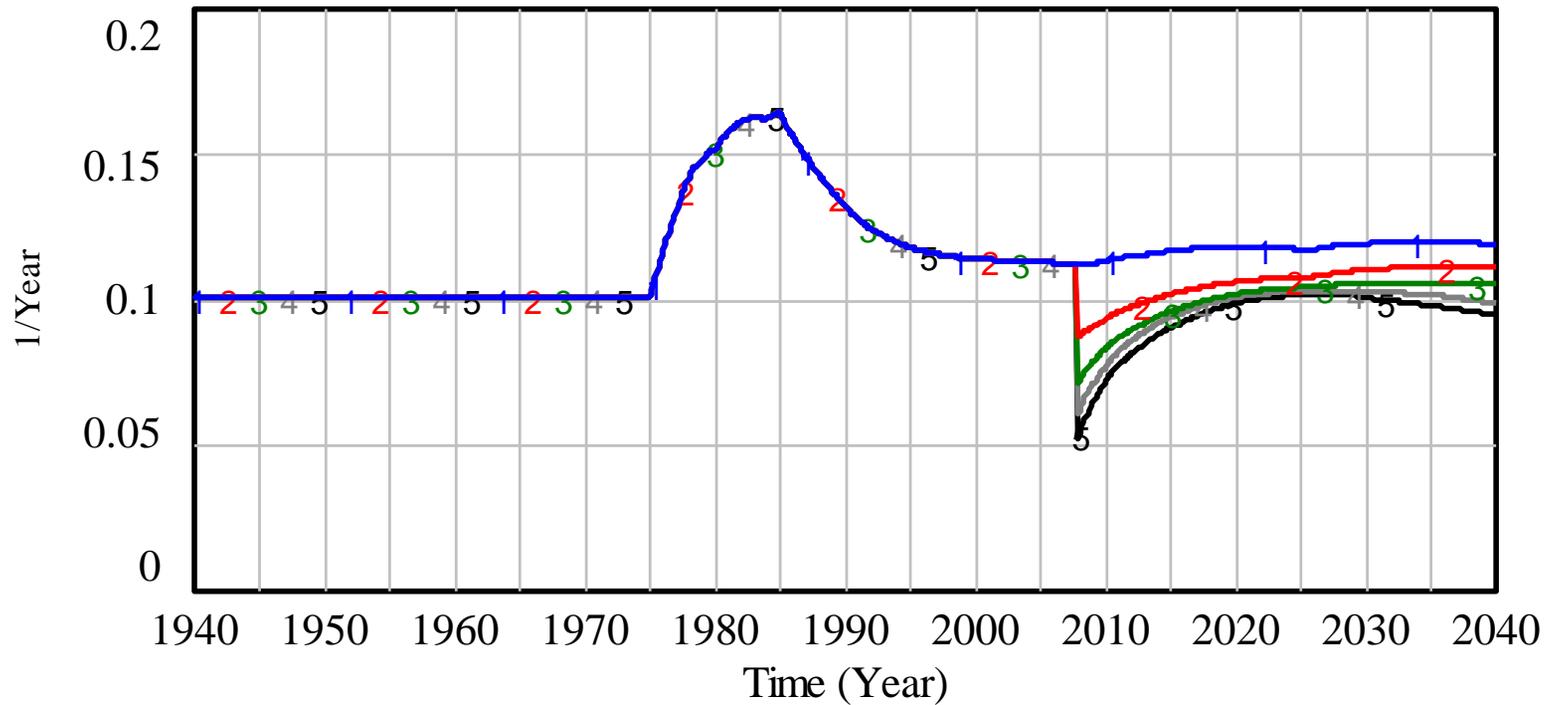


Figure 61: Multiple Fixed Increases Teacher Attrition

Because the current set of teachers receive an unexpected windfall created by the sudden increase in wages, their attrition rate slows significantly. This decreases the number of new entrants that are allowed into the classroom, thus slowing quality improvement of the average teacher.

Percent Classrooms Taught By Qualified Teachers

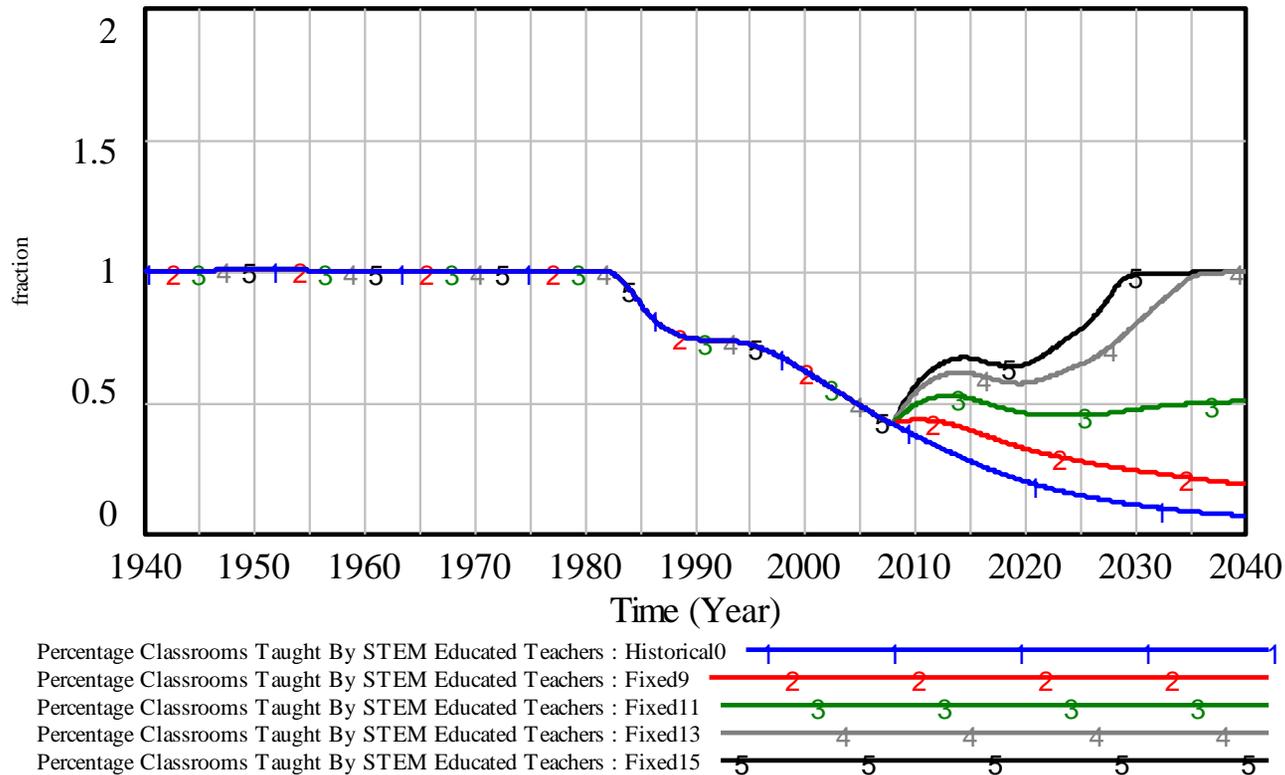


Figure 62: Multiple Fixed Increases Teacher Quantity

Although a much higher percentage of STEM graduates choose to enter teaching, there is still a shortage of STEM qualified teachers for many years because there is a shortage of STEM graduates available to both industry and to schools that is persistent. This is because even though a majority of graduates choose teaching under some scenarios here, there still are not enough of them to satisfy the teacher shortfall. Under the higher wage scenarios, eventually the shortages are abated because enough STEM college graduates are eventually created to fill both school and industry demand. This graph also is indicative of tipping point behavior in the system.

Average STEM Teacher Quality

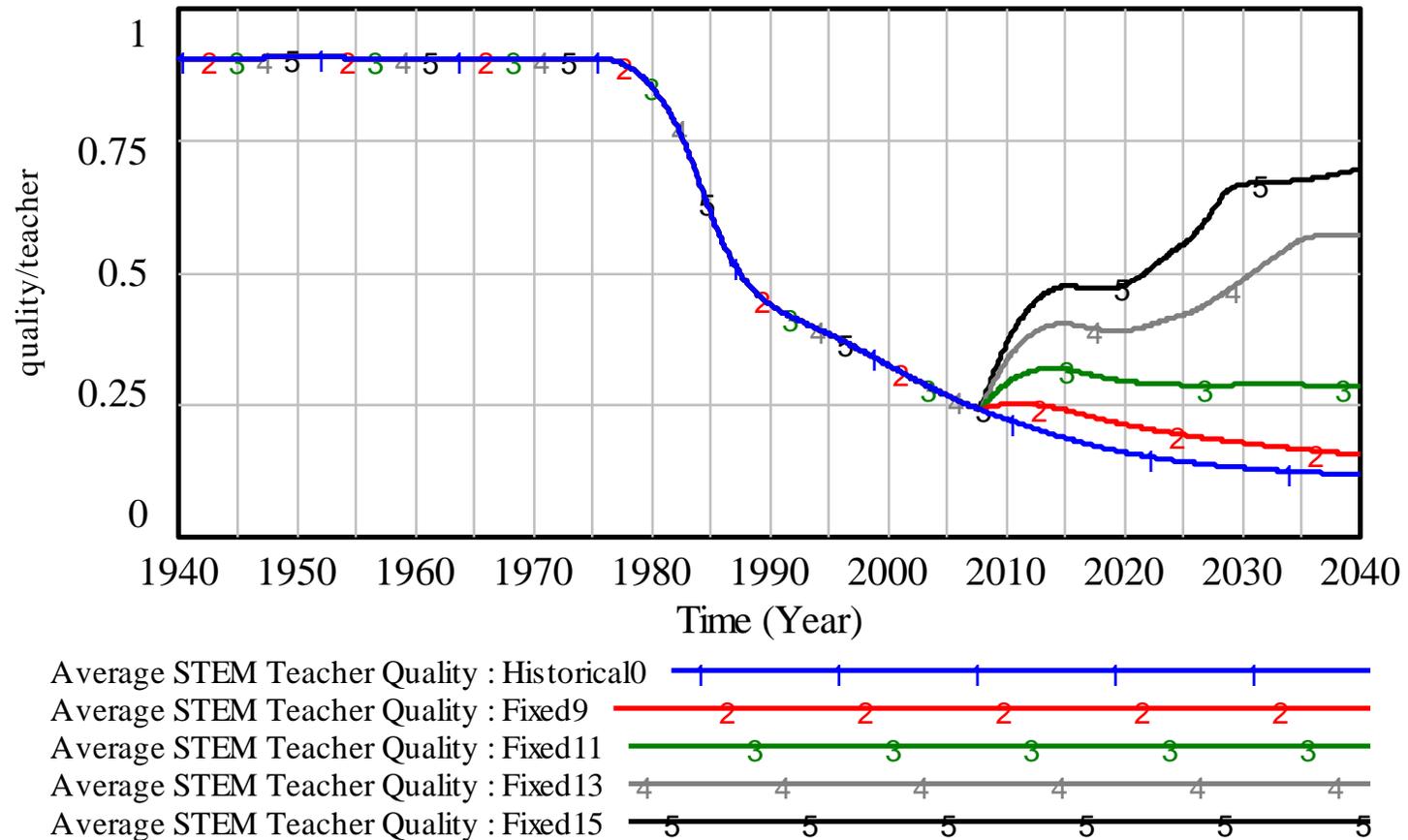


Figure 63: Multiple Fixed Increases Classroom Quality

Average STEM teacher quality is a function of both the quality of STEM trained teachers and the percentage of STEM classrooms taught by qualified teachers. Under lower wage increase levels, quality improves marginally but then continues to decline. Under high wage scenarios quality rises substantially and then continues to climb because the systemic forces are moving in more positive directions.

STEM College Graduation

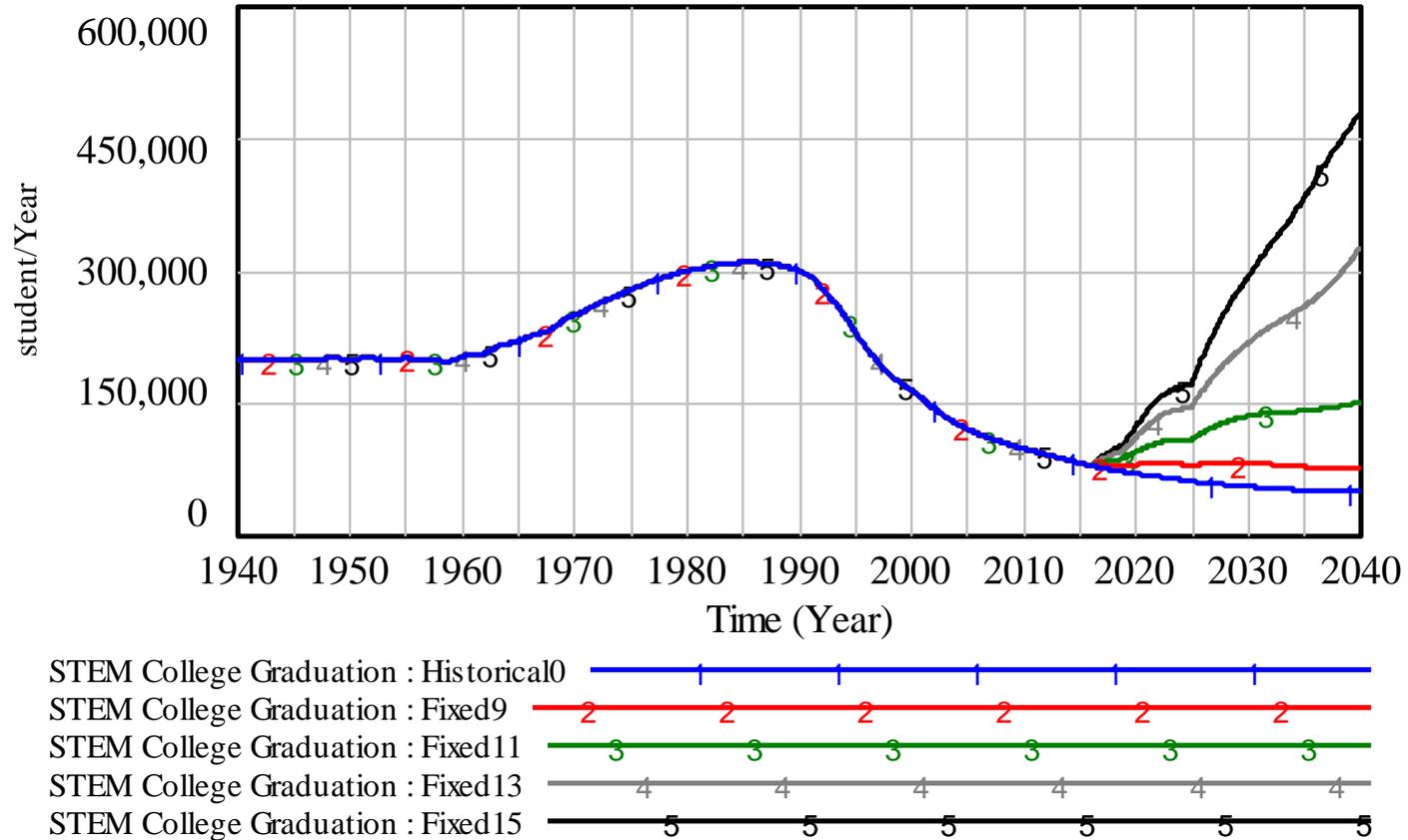


Figure 64: Multiple Fixed Increases College Graduation

The number of college graduates who emerge after the reform in 2008 begins to change dramatically after the year 2013 under some scenarios.

STEM Workers

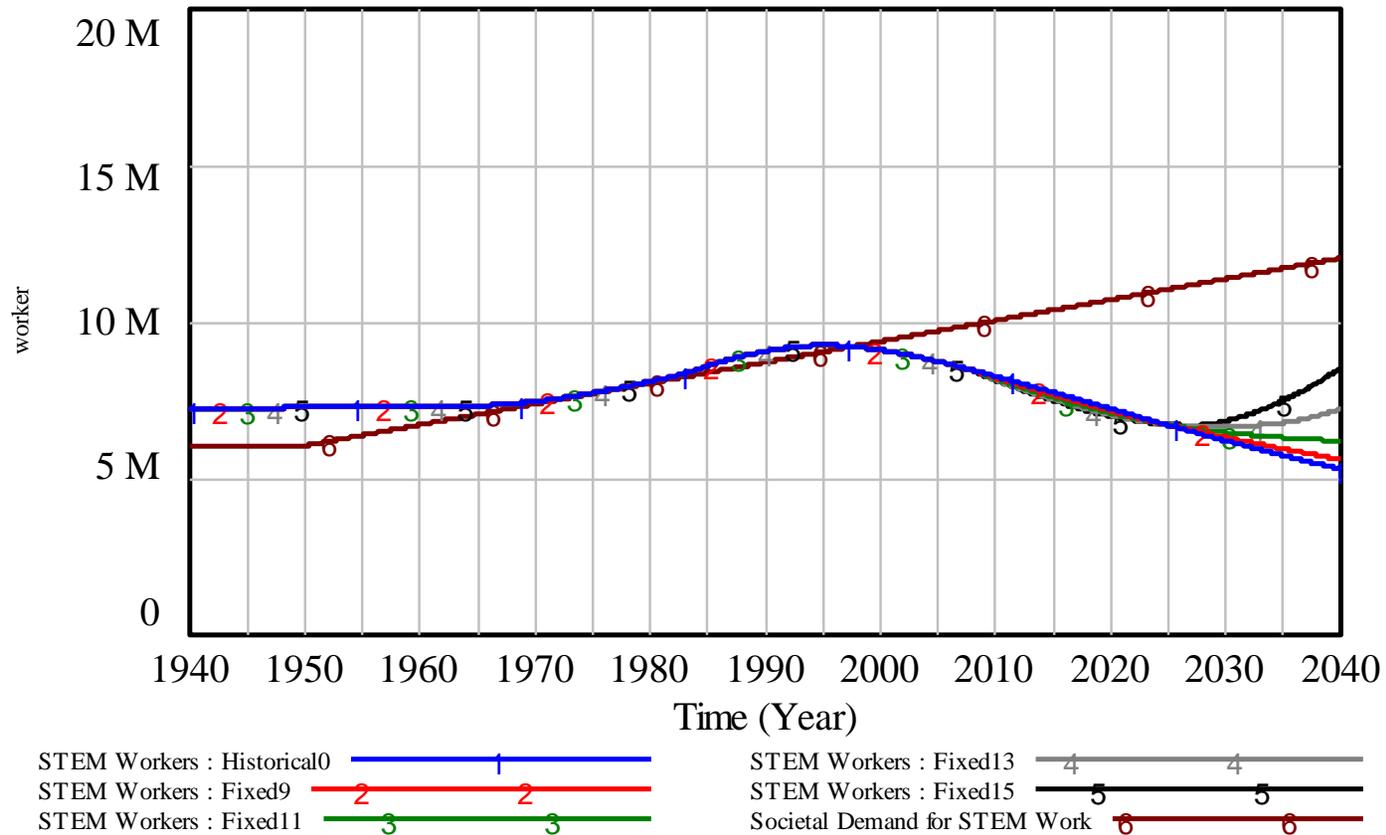


Figure 65: Multiple Fixed Increases STEM Workers

Higher teacher wage increases in 2008 cause STEM industry output to radically change in the year 2028. Note that in this graph STEM workers fill a social demand for STEM work. A larger gap either means that societal demands go unfilled or that these demands are fulfilled by outsourcing technical work to other countries or importing technology. The size of the gap has significant implications for the U.S. balance of trade.

4.3 Competitive Wages

While large fixed teacher wage increases have enormous impacts on the system, it would be good to study a policy that is potentially more stable. The next test examines what would happen if teacher wages are increased to be equal to STEM industry wages. STEM teacher wages respond dynamically to changes in industry pay.

In this graph, teacher wages are shown to be higher than STEM industry pay because of a modifier related to ‘intrinsic teacher reward.’ Monetary compensation is equal, but it is believed that people derive some utility from doing a social good and other lifestyle considerations. This utility is here translated into a dollar value and added to wages here.

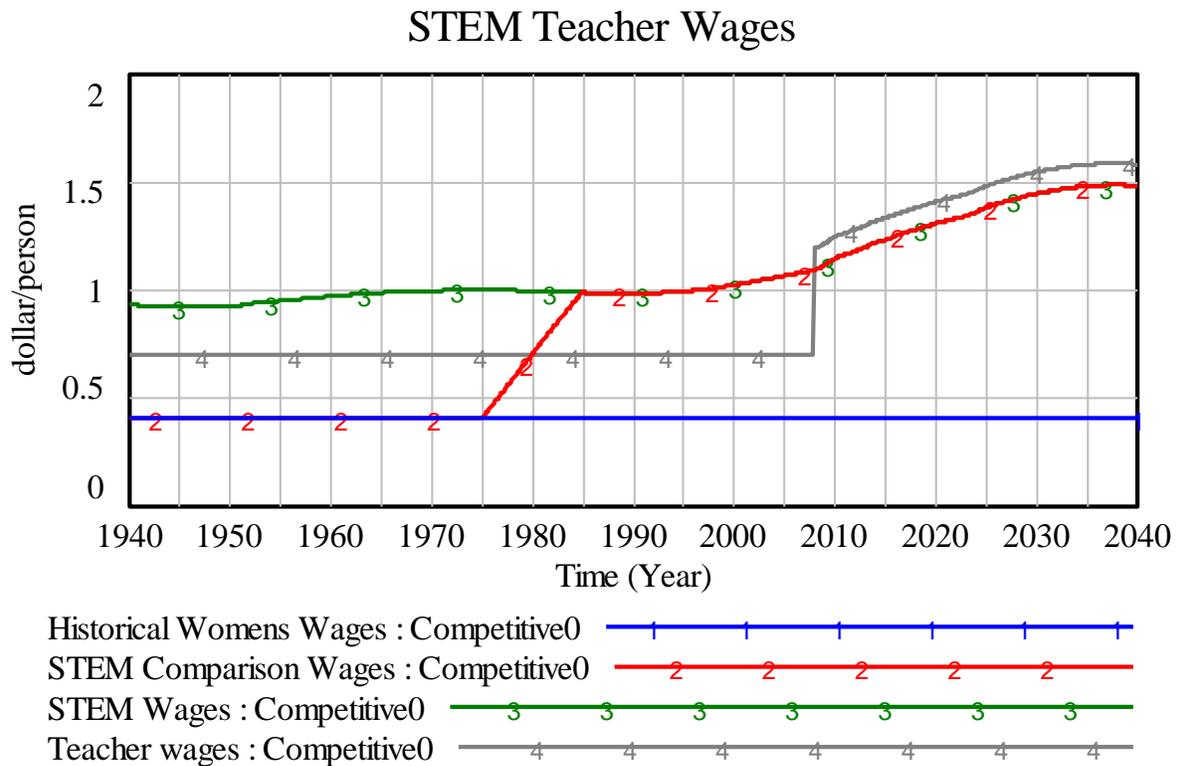


Figure 66: Policy Test Competitive Wage

Teacher compensation steps from current levels to values much higher in 2008. They continue to rise until approximately 2040 while shortages of STEM trained individuals get worse.

Percentage Classrooms Taught By STEM Educated Teachers

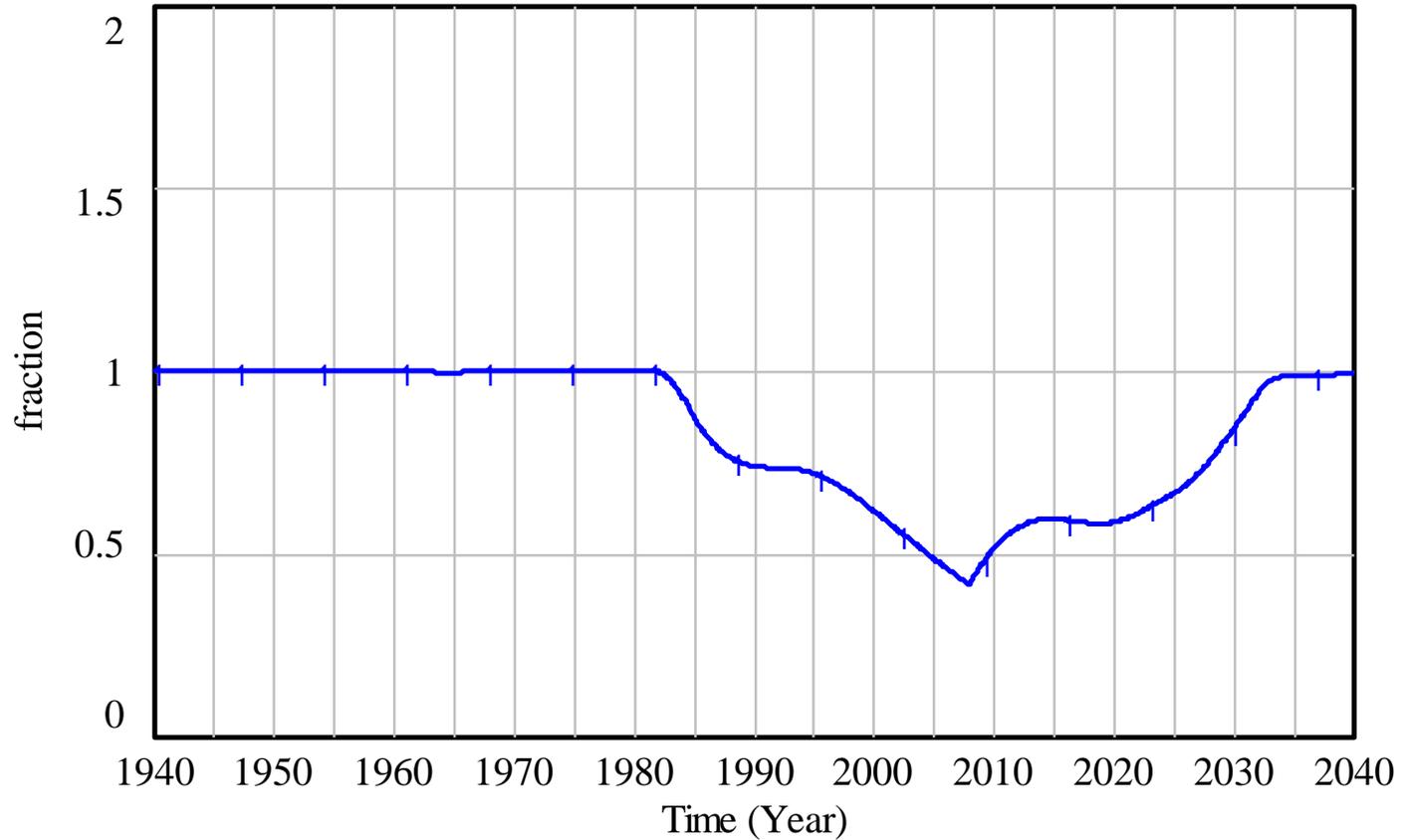
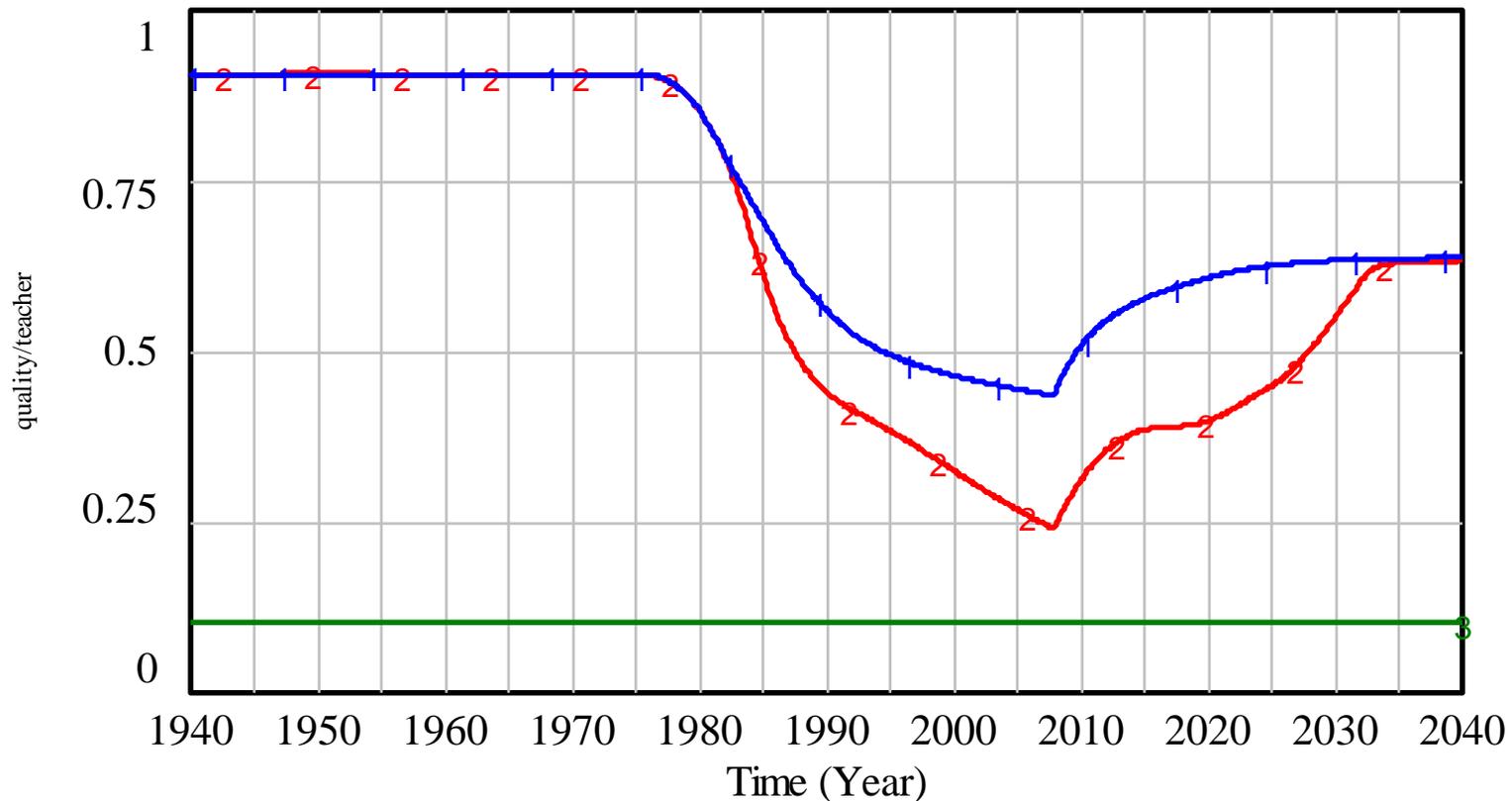


Figure 67: Competitive Wage Teacher Quantity

The percentage of classrooms taught by people with training in STEM subjects rises. In the year 2035, teacher shortages end, and every classroom is taught by a STEM qualified individual.

STEM Classroom Quality



Average Quality of STEM Educated Teachers : Competitive0 ————
 Average STEM Teacher Quality : Competitive0 ————
 Quality of Unqualified Teachers : Competitive0 ————

Figure 68: Competitive Wage Classroom Quality

The quality of the average STEM teacher also begins to rise asymptotically towards a stable level associated with the quality of new entrants that can be drawn by paying wages equal to industry wages. Classroom quality rises to equal the quality level of STEM capable teachers as shortages abate.

Student Behavior and College Graduation

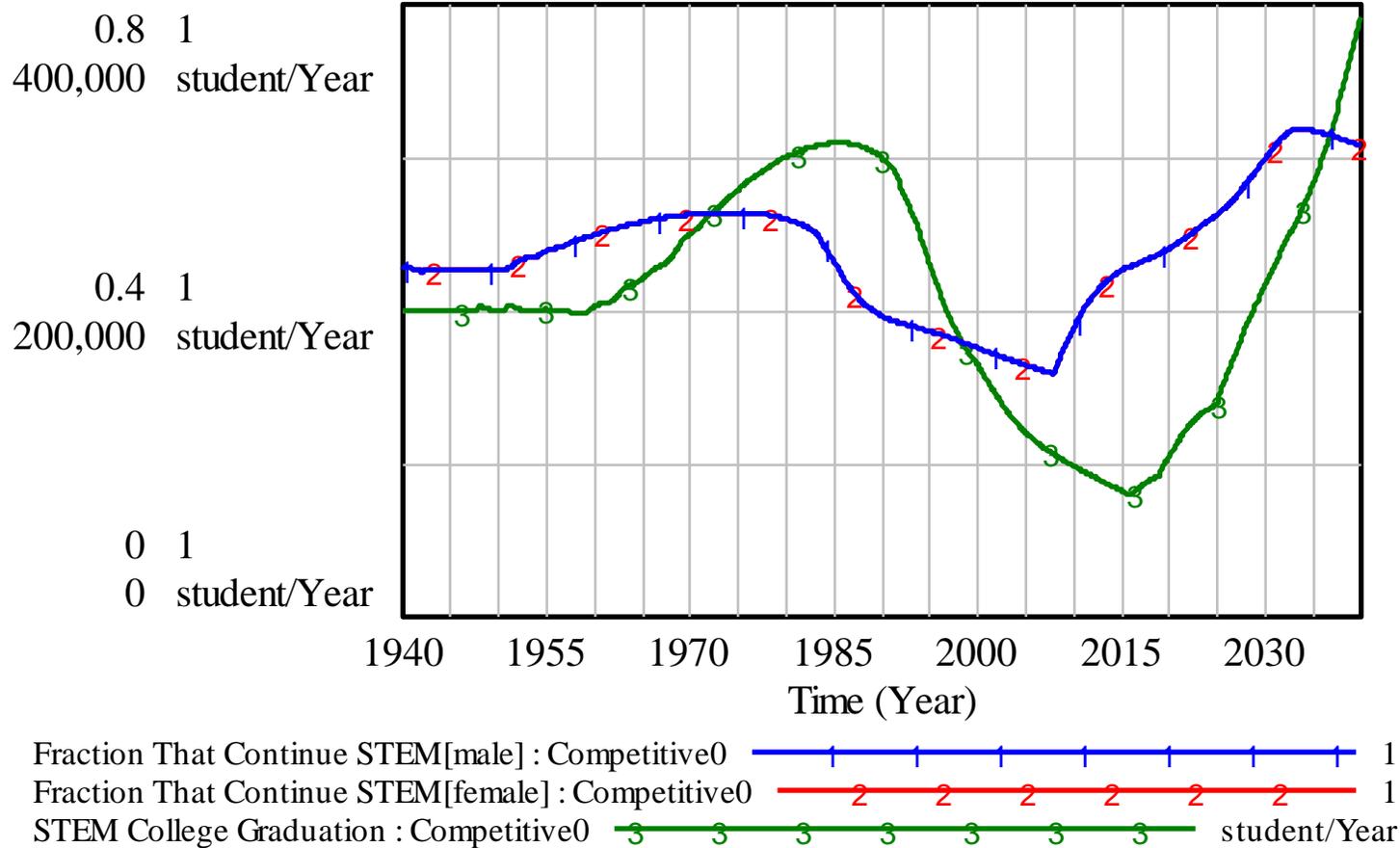


Figure 69: Competitive Wage Student Behavior

The quality improvement in 2008 causes the downward trend of STEM college graduates to reverse in 2016. After that point, the number of STEM trained college graduates begins a rapid ascent.

STEM Workers

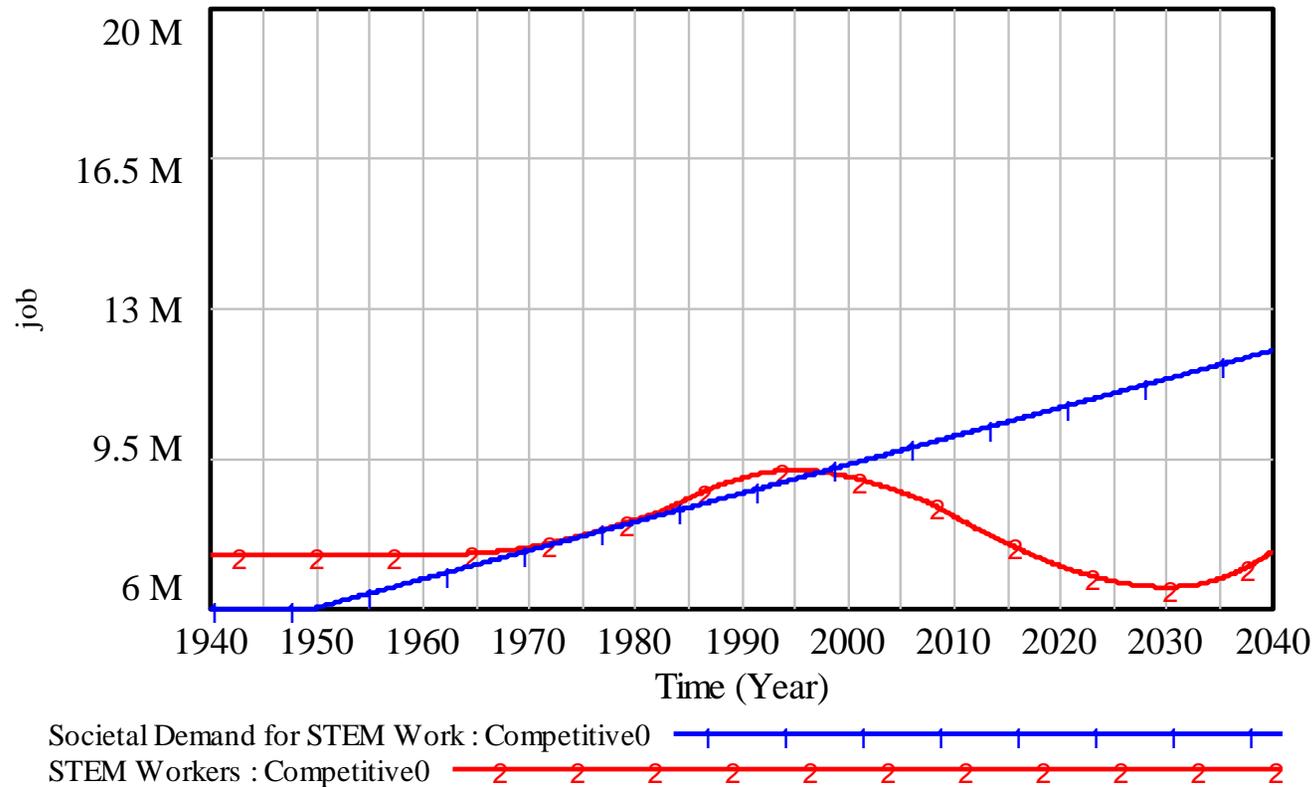


Figure 70: Competitive Wage STEM Workers

While college graduations begin to rise in the year 2016, it is only in 2030 that the number of graduates becomes equal to the number of retirements, causing the number of STEM workers in industry to begin to rise again. It is not until 2040 that industry begins to close the gap between societal demand and industrial output.

4.4 STEM Teacher Wages as a Fixed Percentage of STEM Industry Wages

Tying STEM teacher pay to industry pay made the system more responsive and stable than fixed wage increases that are unrelated to industry pay. The following set of simulations tests various teacher wage policies that fix teacher wages to some percentage of industry pay, but not necessarily equal to industry pay. Pay levels that are tested are wages at 50%, 75%, 100%, 125%, and 150% of STEM industry pay.

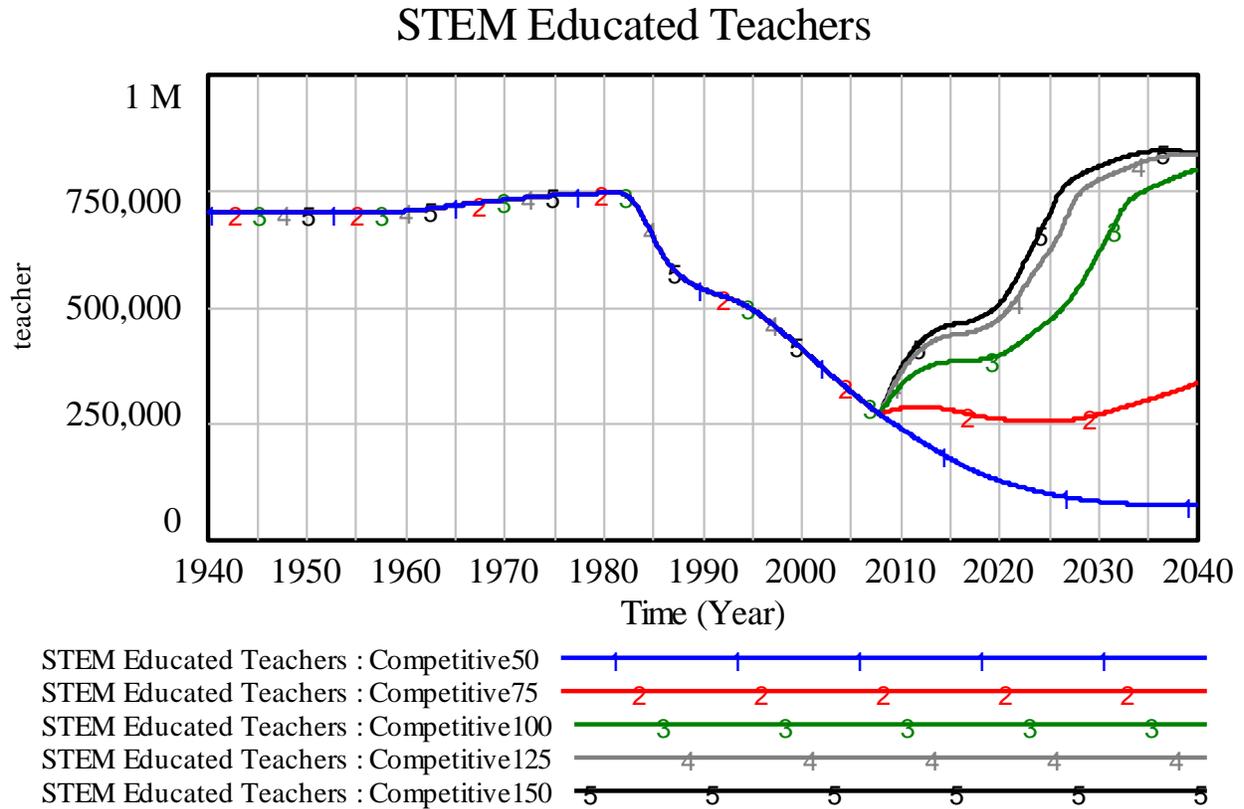


Figure 71: Policy Test Multiple Floating Wages

Higher wage ratios increase the number of qualified STEM educated teachers faster. System response to this policy also exhibits tipping point behavior.

Percent Classes Taught by Qualified Teachers

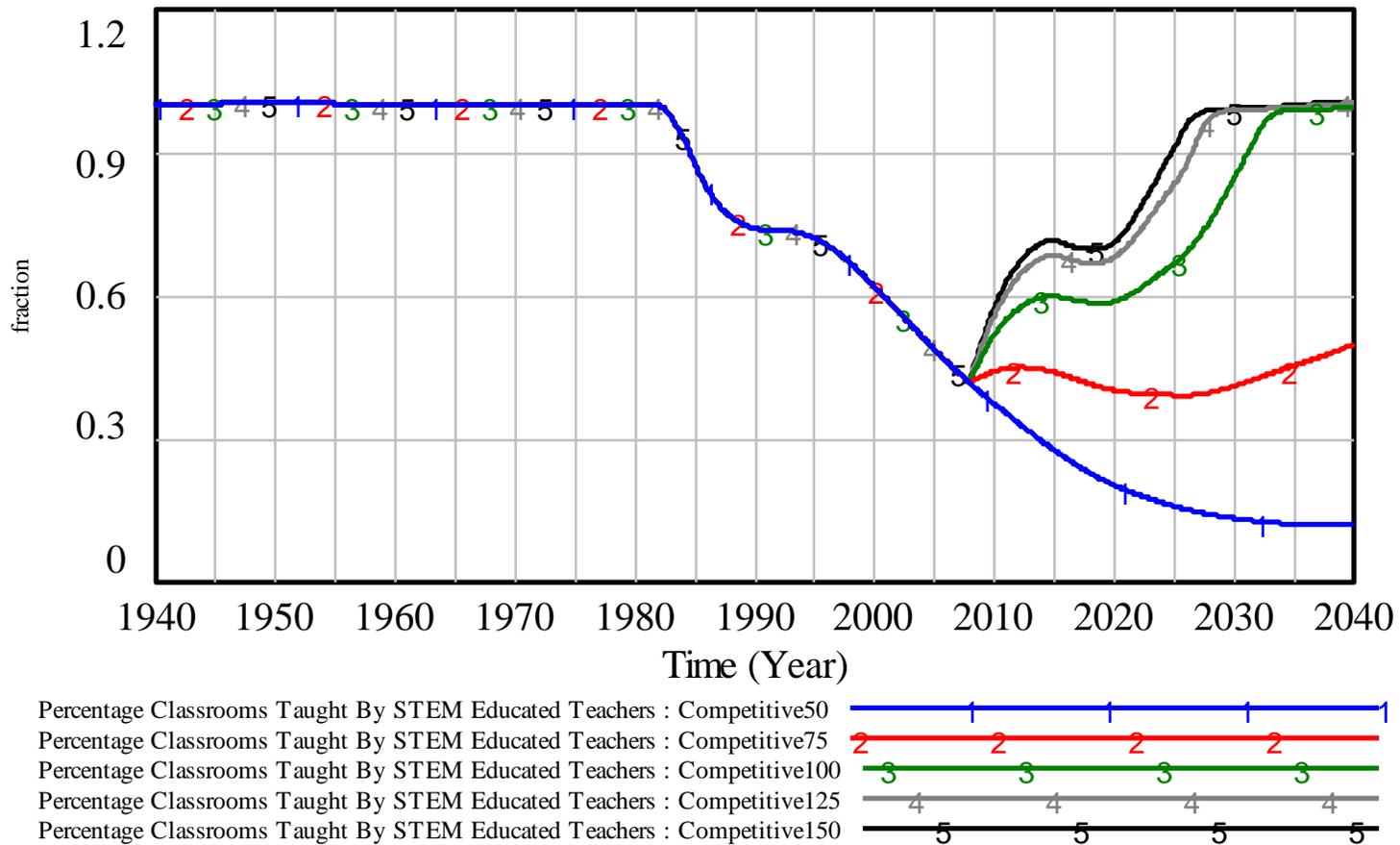


Figure 72: Floating Wages Teacher Quantity

This reduces the number of classes taught by teachers unqualified in STEM. Some ratios are high enough only to arrest the decline, while others eventually cause total recovery.

Average Quality of New STEM Educated Teachers

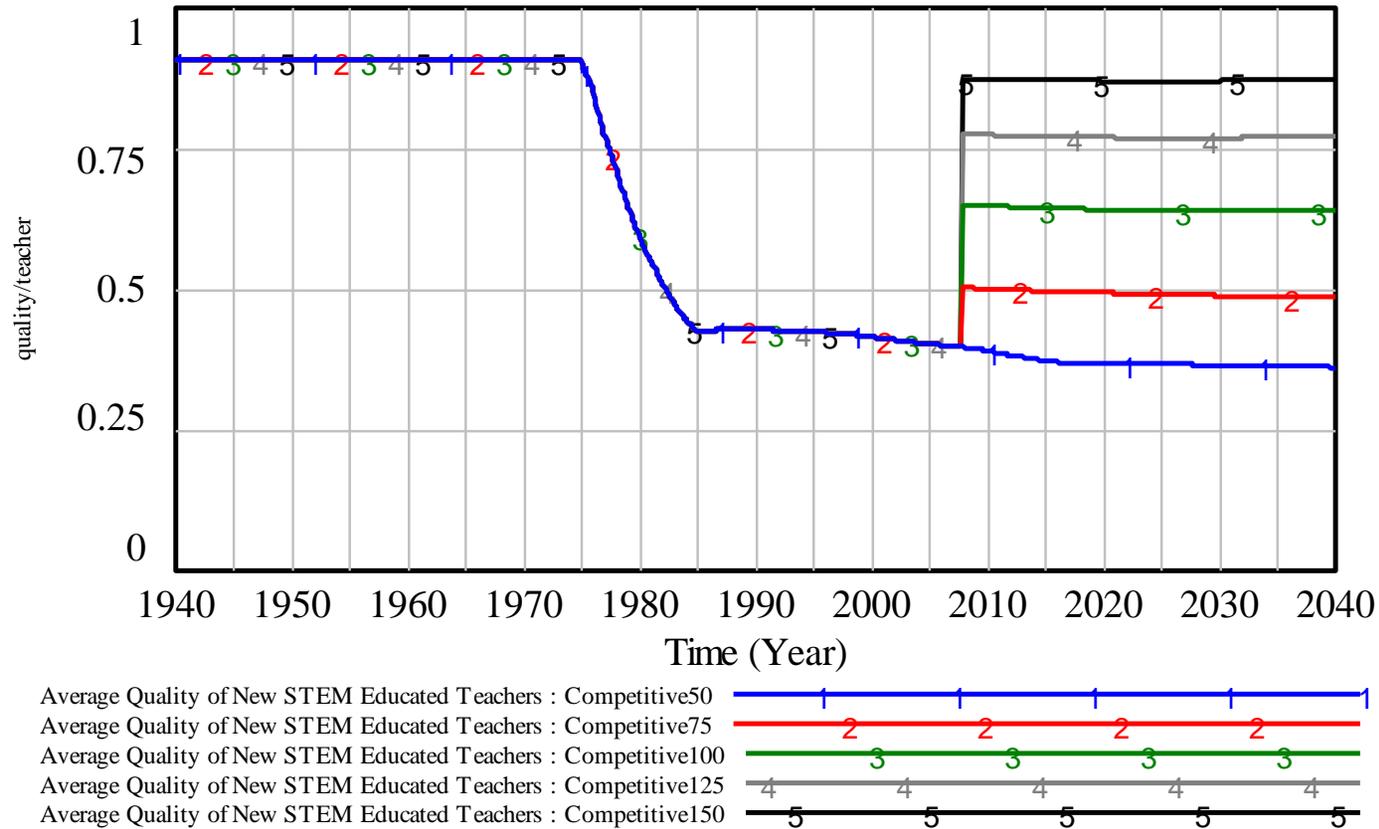


Figure 73: Floating Wages Teacher Quality

In addition to quantity increases, quality increases also occur. These quality increases now are stable over time because it is the opportunity costs rather than the wages of teachers are fixed.

Graph for Fraction That Continue STEM

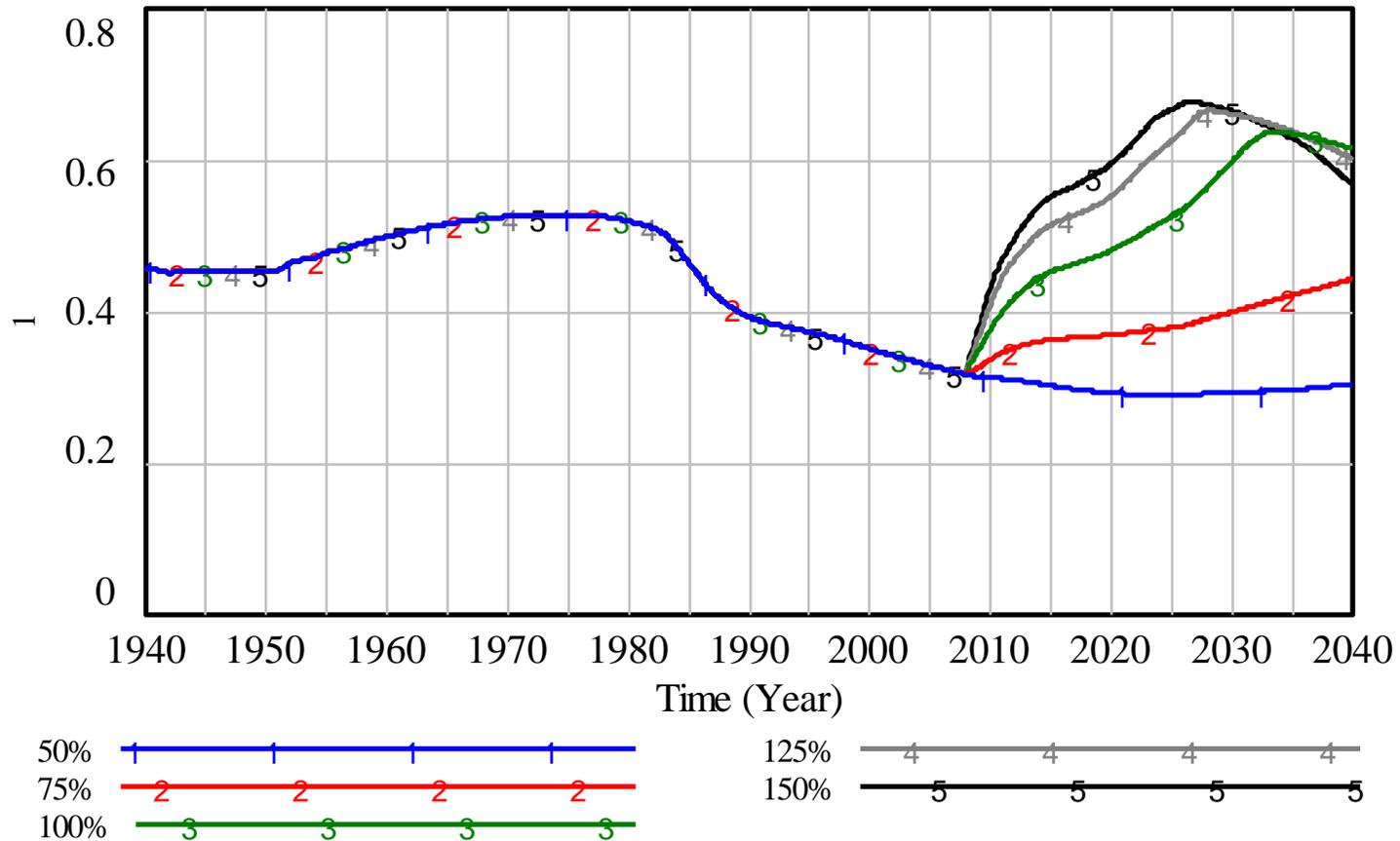


Figure 75: Floating Wages Student Behavior

Higher quality teachers cause the number of people remaining in the pipeline to increase. For some scenarios, this number eventually goes down between 2020 and 2030 because teacher quality is no longer a bottleneck in the system. At this point, the system has “tipped.” These students become less interested at the point because STEM wages go down, not because teacher quality is in decline. The invisible hand of the market rather than the nefarious teacher quality loop is now regulating the societal production of STEM workers.

STEM College Graduation

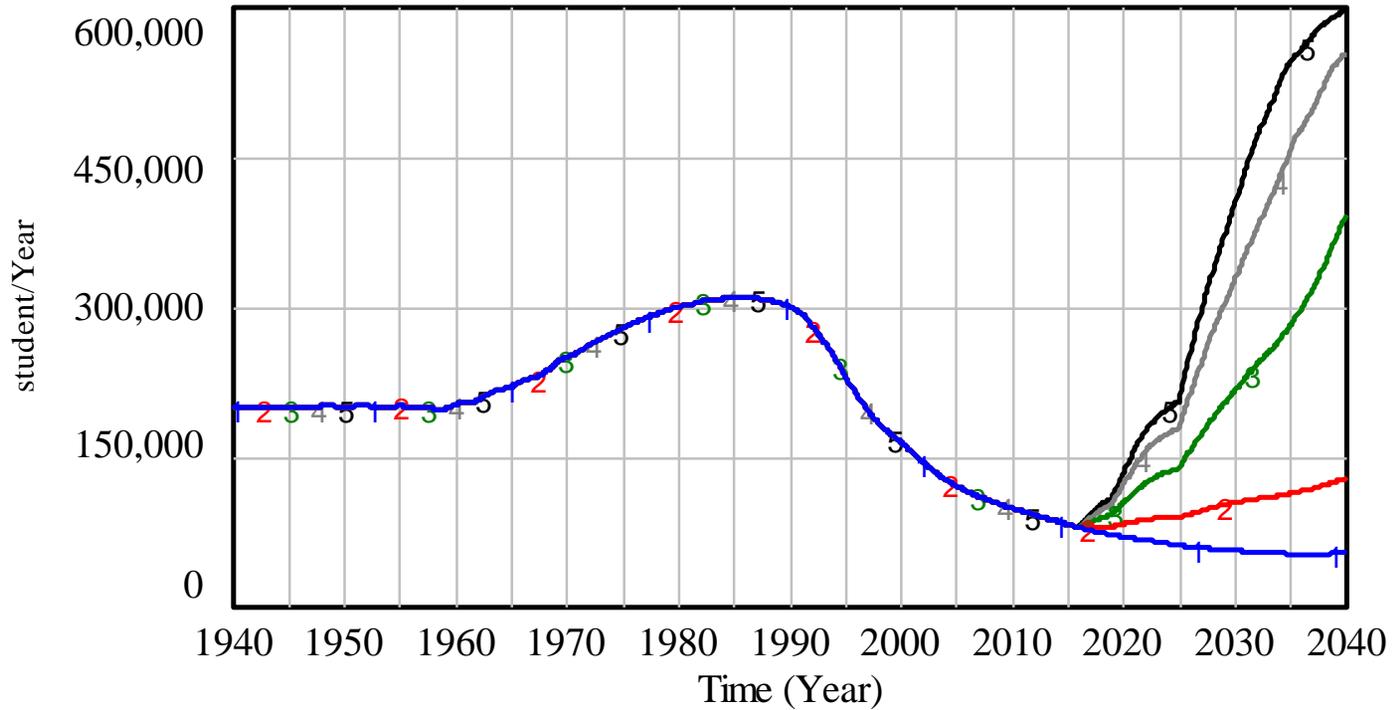


Figure 76: Floating Wages College Graduation

Higher STEM teacher wage ratio increases cause the number of college graduates entering the STEM workforce to increase dramatically after the year 2016.

STEM Workers

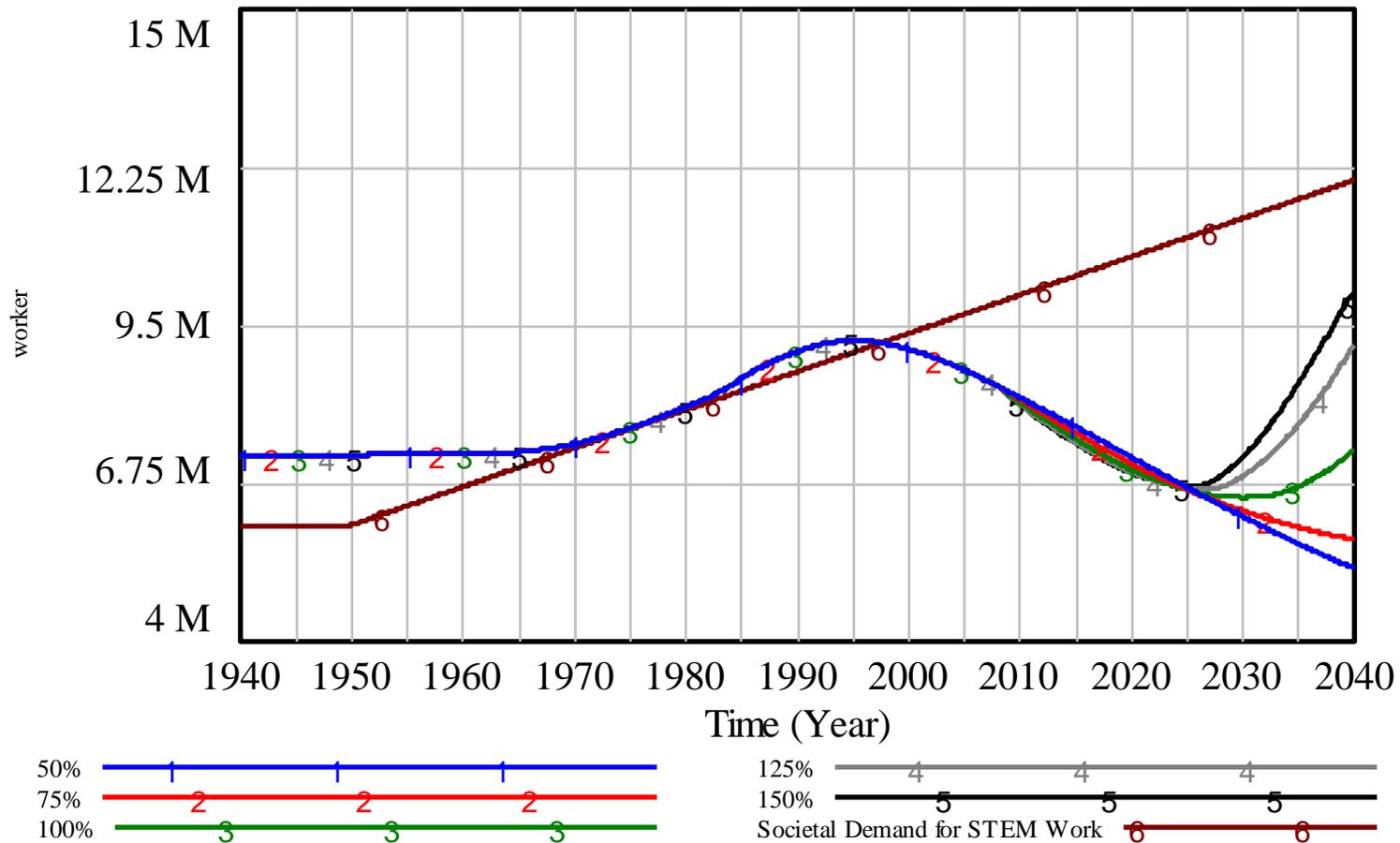


Figure 77: Floating Wages STEM Workers

This policy change in 2008 eventually causes the number of STEM workers in the economy to begin a noticeable recovery in the year 2028. Notice that in the best scenarios **industry shortages actually are worse between 2010 and 2025** because many more of these workers are in the teaching workforce rather than in industry.

4.5 Insights from Policy Simulations

Policies to increase teacher pay by a small amount had virtually no impact in the simulations. Large teacher increases on the other hand were able to move the system past a “tipping point” causing it to operate in a fundamentally different way. In the current state, the number of STEM graduates is largely controlled by the “teacher quality loop” rather than the invisible hand of the market. This means that the market is not responding “rationally” to the wage signaling mechanism. A threshold must be passed so that the structure regulating college outflow is actually more sensitive to market demand rather than teacher quality. Such a transition would take considerable investment in education, and the benefits would not be fully felt for many years because of a transition period in which higher quality teachers would slowly enter schools and an entire generation of more STEM capable children would be grown.

Teacher pay is the current constraint causing less than desirable STEM industry productivity, while STEM industry wages are the current constraint on teacher quality. In order to break this negative cycle, teachers have to be of high enough quality that they can eventually produce enough STEM graduates to meet domestic retirements, meet business growth demands, and to fully populate the educational system. A tipping point must be crossed so that these gaps begin to close rather than widen further. If teacher pay is high enough to draw a substantial number of quality people out of industry in the short term, then in the longer term the educational system will start to eventually fill this gap. If the system begins to “tip” in a more positive direction, it will mean that the positive feedback loop in the system is spinning in the opposite, more beneficial direction. Teacher quality will be high enough that many more STEM graduates are produced every year. Although industry and schools still split this pool of graduates, there would be many more people to split. If the raw number of STEM qualified individuals going into teaching rises as a result of this feedback then the system will be reinforcing in the opposite direction. The positive loop will begin to look like a “teachers creating teachers” loop. High quality teachers will produce many graduates, eventually expanding the pool of qualified teachers, thus increasing the quality of teachers, further increasing the number of graduates.

If teacher wages do not raise enough to cross the “tipping point,” then the system may appear to get better in the short term, but ultimately progress will peter out and fail to positively impact size of the U.S. STEM labor force.

The other significant feature displayed prominently in these simulations is the incredible amount of inertia in the system. While the presence of a tipping point means that investments today can have enormous impact on the future of the U.S. economy, these investments may not come to fruition for decades. It took a considerable amount of neglect for a long period of time to get us into the current mess. It will take a long time to get out of it.

For example, after the policy changes in 2008:

- College STEM graduations began to rise in 2013
- At the earliest, STEM teacher shortages were erased by 2025
- The number of STEM workers in the economy began to rise between 2025 and 2035

Finally, one very important feature to notice about all successful reforms shown so far is that the number of STEM workers in the economy gets worse before better. The people that are not in the economy

raising productivity and U.S. GDP are instead busy as teachers. After fifteen years, the fruits of their labor pay off in a qualitative change in the output of new STEM workers.

5 Final Insights and Conclusions: America Disrupted?

This goal of this work was to uncover a cause for the decline in the number of engineering graduates that has taken place since 1985 despite the fact that engineering wages have remained incredibly strong and engineering unemployment was extremely low during that time period. This presented a paradox that was hard to understand. It seemed that the law of labor-market supply & demand was being violated in some fundamental sense. By going through a system dynamics modeling process, I was able to devise a plausible model that is capable of reproducing historical system behavior in a qualitative sense. I identified a positive feedback loop that can cause normal market mechanisms to turn against themselves leading to market failure.

The process of building and simulating the model moved research in many originally unintended directions leading to insights including the following:

- The STEM educational system is structured as a “gauntlet.” The unique hierarchical or sequentially structured nature of mathematics knowledge leads to a situation in which students that fail to keep up will most likely never end up as scientists or engineers. Efforts at educational reform in STEM should therefore focus on putting in place an intact continuous pipeline of quality math educators throughout K-12. Unlike humanities subjects, the impact of a lone inspirational mathematics teacher can only be minimal. Low quality at any one point in the pipeline may invalidate the effectiveness of good teachers at every other point in the chain.
- The length of this pipeline leads to considerable delays when responding to economic signals. The decision to pursue a Law degree can be made during college, but failing to keep pace in elementary school mathematics can forever exclude a person from a STEM career. Over 80 percent of people have been effectively excluded from engineering before entering high-school.
- Although the market for STEM workers generally functions as a “free-market,” the extremely high barriers to entry caused by the constraints imposed by the “gauntlet” and by poor teacher quality are effective at keeping wages extremely high. Many of these barriers are caused by inequality of educational opportunity. Those children who are not in a school with an intact pipeline of quality STEM educators are much more likely to fail. These children are effectively excluded from a chance at social mobility. Because our society embraces a system of economic justice predicated upon the notion of “equality of opportunity” rather than “equality of outcomes,” these results should give us pause. Effectively excluding racial minorities and the economically disadvantaged from STEM careers by failing to provide an intact STEM pipeline in elementary school can be viewed as a civil rights issue.
- By paying teacher wages that have no relation to subject matter, we impose the highest opportunity costs on bright individuals in high-paying fields. The educational system is therefore

systematically set up to produce the poorest proficiency in skills the economy deems most desirable.

- The drop-off in the number of engineering graduates that began in 1985 had nothing to do with the year 1985 itself. It happened because the damaging “teacher quality” loop was activated and strengthened by three things that occurred in the 1950’s, 1960’s, and 1970’s. Firstly, the Cold War increased the demand for STEM skills, raising the wages of STEM workers and the number of STEM workers the economy desired. Secondly, gender role liberalization combined with declining teacher pay and status caused teacher quality to plummet. Finally, unionization erased any correlation between teacher pay and student outcomes. These three impacts all contributed to setting the devastating feedback loop explored here in motion.
- The architectural relationships between the American systems of government, K-12 education, academia, and industry are set up to systematically under-develop the quantitative and analytical skills that the economy desires most. We are trapped by a positive feedback loop that is operating in a nefarious manner. Higher industry wages result in lower quality educators in the short term, and lower quality educators cause higher industry wages in the long term.
- The positive feedback loop in which we are currently trapped can be induced to operate in an opposite, more beneficial manner. In order to cause this qualitative shift in system behavior however, investment in reform must be sufficient to move us past a “tipping point.” If investment in education is sufficiently strong, it may create more STEM college graduates. If many more STEM College graduates are produced, then more of them will choose to go into teaching. If reducing shortages raises quality, and raising quality reduces shortages, then the same loop will be operating in a direction that is highly beneficial for our schools, domestic technology-based industries, and U.S. economic health.

In order for STEM teachers to be drawn from the ‘best and the brightest’ today they must be paid accordingly. Because previous generations both invested more in education and could rely on a trapped labor pool, they provided their children with excellent educations. The ‘baby-boomer’ cohort was the last generation to receive this substantial gift from its parents. Spending the money to return high-quality educators to our schools is perhaps the most efficient investment our society could make in its long term economic health. *This is not a mere platitude* – the reinforcing causal mechanism shown in this paper can dramatically impact the dynamics of the system – both for better and for worse. However, this would require sustained effort and willpower. At times things could appear to get worse in the short-term before they get better. The existence of a tipping point in the system implies that small incremental fixes to the system could have no lasting impact. Effects may only be felt if both wage levels and incentive policies are both altered dramatically and sustained for multiple decades. The wounds we are now experiencing were inflicted over many years and cannot be healed overnight.

One final question that must be asked is: “could America be disrupted?” The combination of poor student performance, increasing math illiteracy at a societal level, high STEM salaries, and STEM labor shortages will necessarily lead to increased outsourcing and a worsening balance of trade. The societal demand for the output of STEM labor will not simply go unmet. If the STEM labor force situation gets bad enough, there are plausible scenarios in which the U.S. could be transformed from an economic powerhouse into a cottage industry simply because our society was incapable of thinking beyond the next fiscal year or

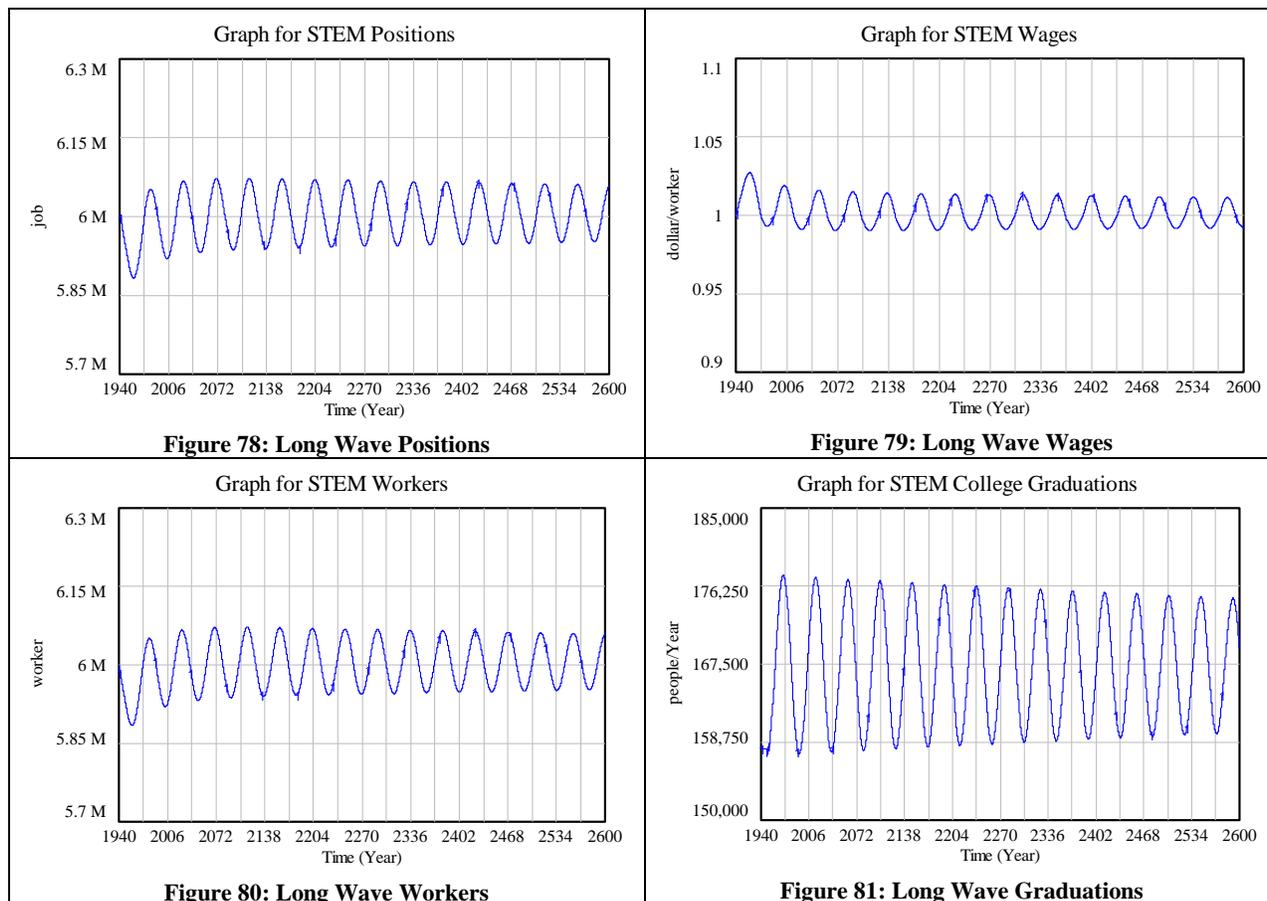
election cycle. If this happens, we are likely to seek out scapegoats. Unfortunately, blaming foreign competition for our own failings in this regard is as tempting politically as it is useless. If we fail to remain globally competitive in high-tech it will be because we destroyed ourselves. The problems we now face were entirely self-made.

Appendix A: Potential Areas for Future Modeling

This model can be expanded in many useful ways. The following is a partial list of feasible extensions:

- A more detailed structure for understanding the relationship between teacher quality and teacher turnover should be built.
- The impact of foreign workers in U.S., foreign students in U.S. institutions of high education, outsourcing, and foreign competition should be included. Currently in the model it is possible for STEM wages to rise to levels that would not truly be practical. Higher STEM wages should trigger increased outsourcing and strengthening foreign competition.
- Gender related issues could be explored in the model. Male and female STEM track students could be split into two separate structures and the rate of advance or ‘falling out of the pipeline’ can be treated separately by gender. The concepts of sex differences in ‘self-efficacy’ and planned behavior can be explored within the context of the model. Similar work could be done to look at issues of race and ethnicity.
- Behavior in the pipeline can be expanded to include other things impacting perceived behavioral control, social norms and individual preferences. Some things to look at could include socio-economic status and the importance of role-models.
- Currently the model does not represent variation by geography or desirability of a school or school district to teachers. Geography based dynamics could be introduced to study the impact of teacher turnover based on the desirability of living in different locales.
- Quality should be modeled separately at different grade levels based on the characteristics of effective STEM teachers at those different levels.
- Quality and attrition at the university level should be incorporated. The conflicting demands of teaching and conducting research should be considered.
- Dr. Stuart Rojstaczer, formerly at Duke University, provided the following information: In the 1960’s the typical university student studied 26 hours outside the classroom. Today the same student studies for 12 hours. Meanwhile, the average GPA has gone up substantially. In addition, humanities majors have a GPA that is 0.4 higher than the typical engineering student. Create a model that incorporates the dynamics causing an upward shift in GPA known as grade inflation. Does this cause the decreased hours of study? Do higher GPAs and less hours of work translate into exodus from engineering at the university level?

Appendix B: Kondratieff Long Wave?



One feature of the dynamic behavior of the model that was unexpected is that the model produces consistent oscillations with a periodicity of approximately 50 years under some circumstances. This may be significant because many economists have put considerable effort into documenting and explaining the existence of economic “long waves” with approximately the same periodicity. The existence of such waves was first posited by Kondratieff (Kondratieff, 1935), and the idea was brought back in more recent history by Schumpeter (Schumpeter, 1939), who popularized the idea of “creative destruction.” (Schumpeter, 1942) They have been studied extensively by Freeman (Freeman, et al., 2002), Perez (Perez, 2002), and Sterman (Sterman, 1985) among others. Many studying the issue assert that periods of radical technological innovation in industrialized capitalist economies tend to recur approximately every fifty to sixty years. Many of the current explanations for the wave attempt to tie it to the functioning of financial markets, the availability of capital, the rate at which society is capable of absorbing and diffusing technological change, and the reaction of the political system to periods of “irrational exuberance” and the ensuing “busts.”

When simulating a model containing only the “STEM Gauntlet” and “Invisible Hand Loops” structure depicted in Figure 18 and Figure 20 for over six hundred years, the following pictures emerged. While these oscillations did not occur under all sets of initial conditions and parameters, most models resonated at similar frequencies even if their oscillations happened to dampen rather than continuing forever as depicted here. In these runs, all exogenous parameters used to influence the model remained *constant* over time. This behavior is internally generated by the structure of the system.

Students in the STEM pipeline at all ages (K-12 and university) either continue to study mathematics or fall off based on the current wages of STEM workers that are observed while they are in school. After a considerable delay, these students emerge to become STEM workers. As discussed previously, students who fall off the pipeline at any stage are not allowed to reenter it even if later market conditions improve. The wages of STEM workers climb if this demand is not met by current labor force levels and fall if there is an excess of workers. The number of available jobs increases if STEM workers are cheaper and decrease as wages rise. In this sense, the market “clears.” Technical jobs and workers try to match at a prevailing wage. If there is a mismatch, wages (rather than workers) tend to adjust because the supply of workers can only be influenced by the extremely long-term functioning of the STEM pipeline. STEM employers cannot use substitutes from the pool of non-STEM capable workers in this model.

The oscillations presented here have a periodicity of approximately fifty years. The length of this wave is highly sensitive to length of the educational pipeline. The time it takes to educate someone before they can become a productive STEM worker is set to be around 17 years in the model. These oscillations produce generational spurts in interest in STEM that are followed by periods of ambivalence when the market for STEM labor becomes saturated with more senior workers.

Here I present a hypothesis for the technological long wave which I believe to be novel. I propose that neither financial markets nor political systems create innovation. Technologists create innovation. Capital chases that innovation. The attractiveness of STEM work at any time influences both the quality and quantity of people emerging from educational institutions many years later. The quality and quantity of employed STEM workers at any point in time determines the rate of technological change that is possible. The periodicity of the technological long wave is largely influenced by the length of time it takes to train a child to effectively contribute in STEM fields and the limitations imposed by the sequential and hierarchical nature of mathematical knowledge itself.

Appendix C: Simulation Model Structure

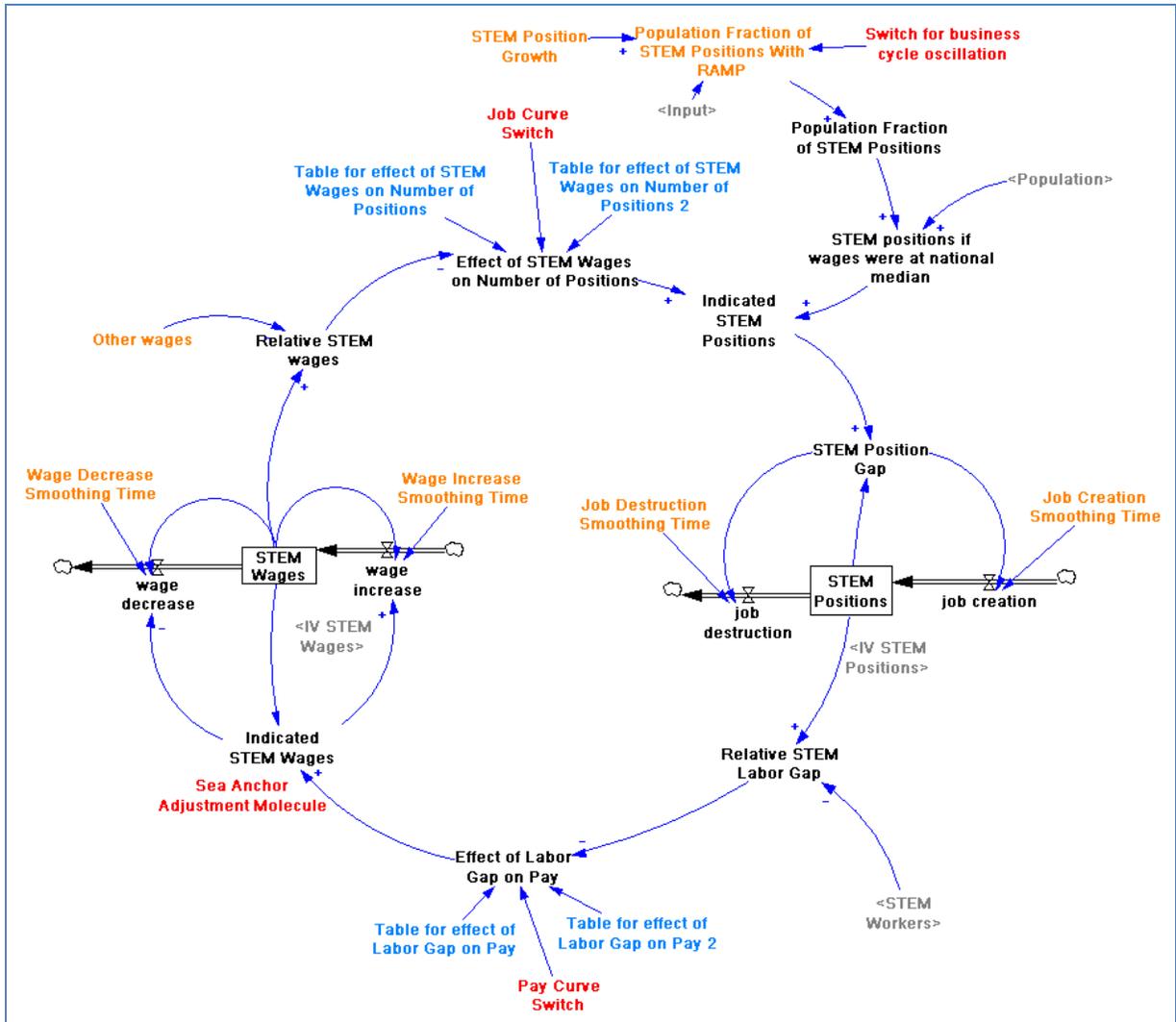


Figure 82: STEM Labor Demand and Wages

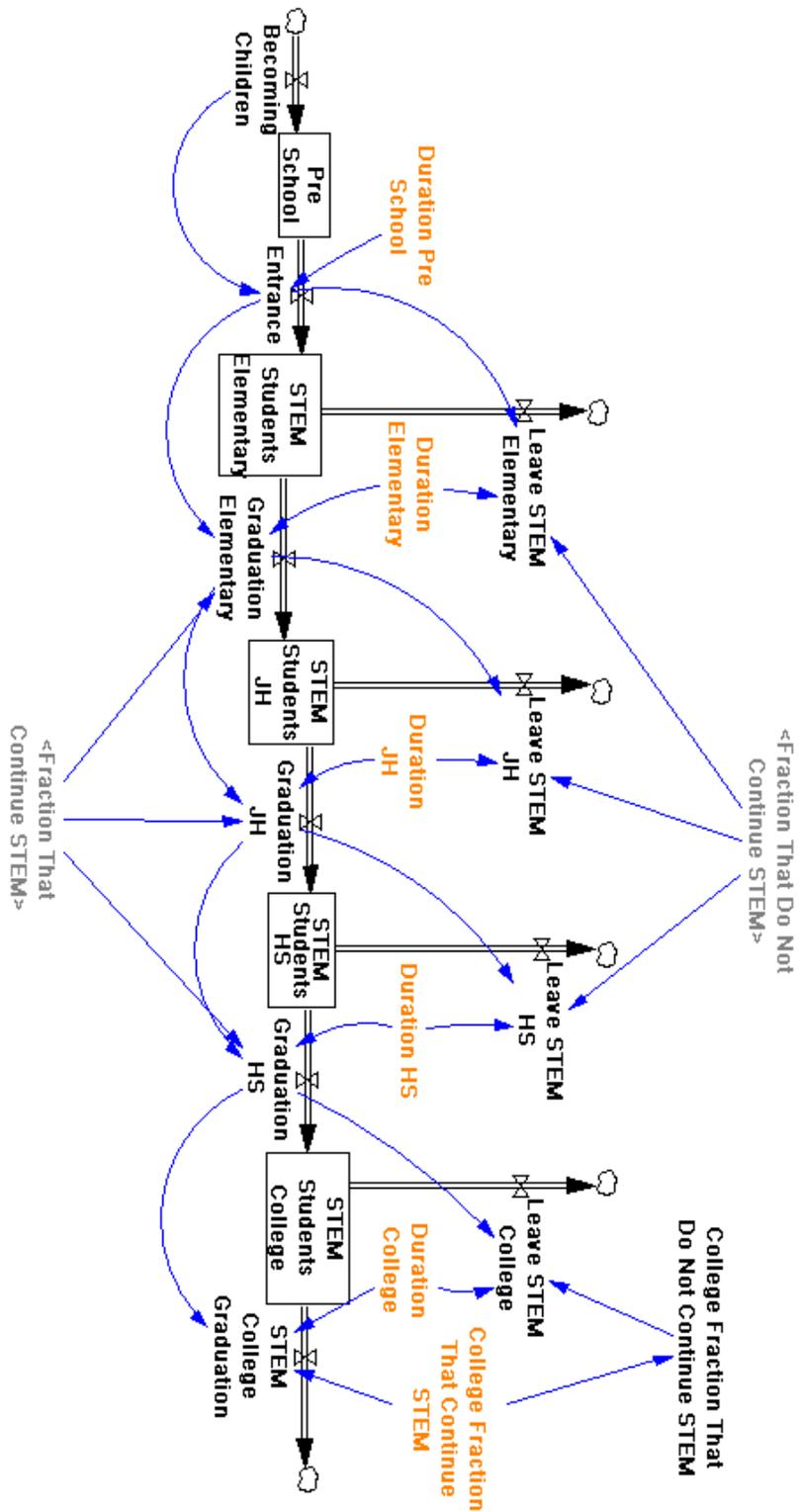


Figure 83: STEM Education Pipeline

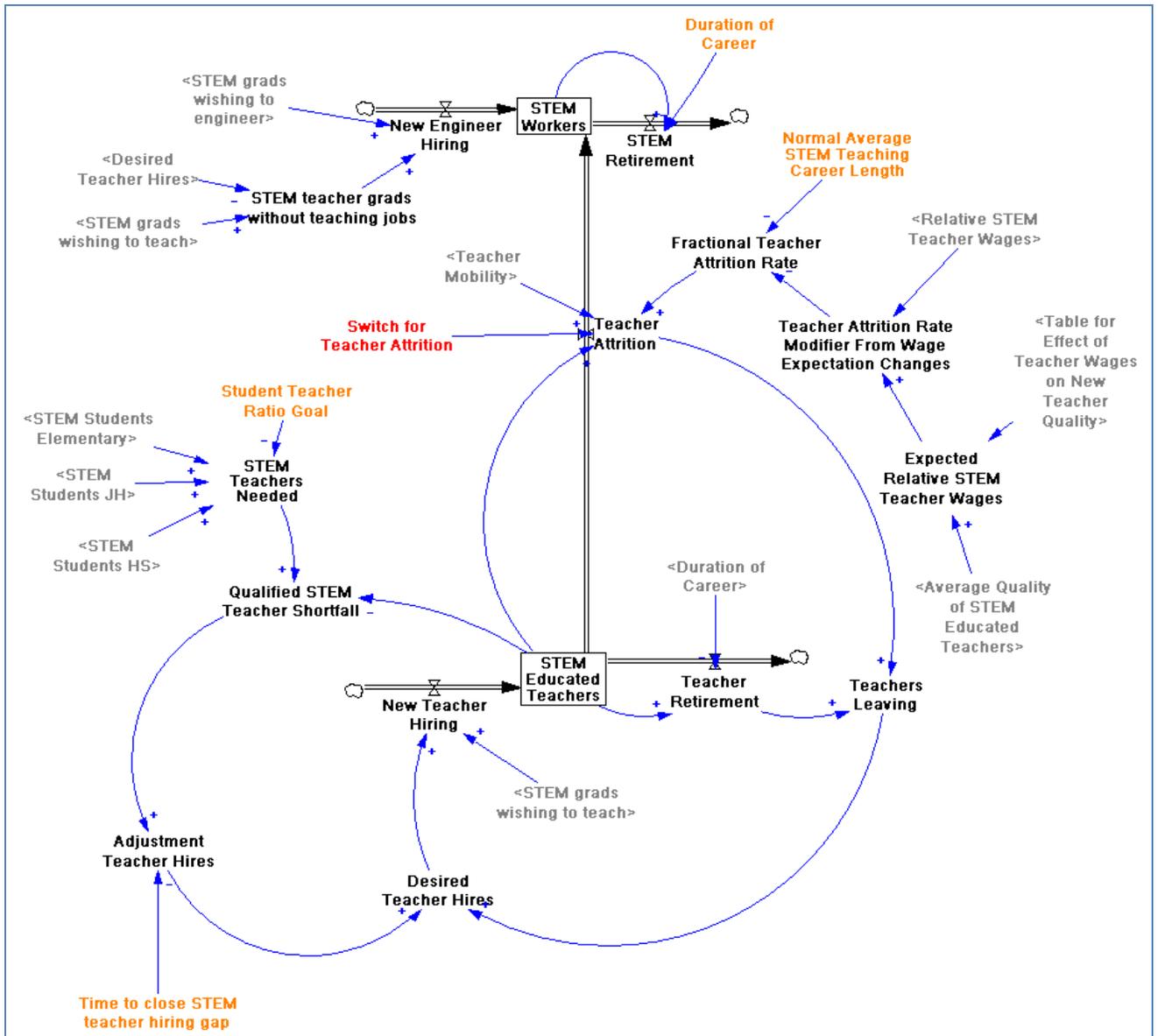


Figure 84: STEM Workers and STEM Teachers

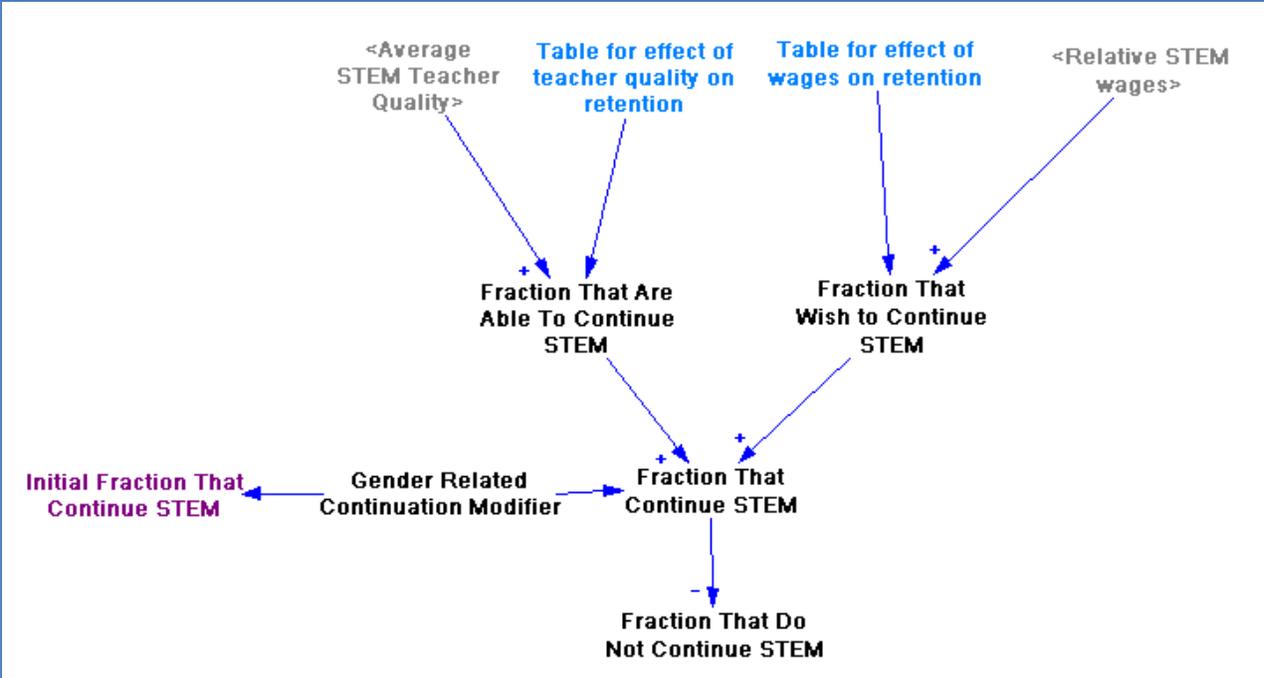


Figure 85: Student Behavior from Intent and Control

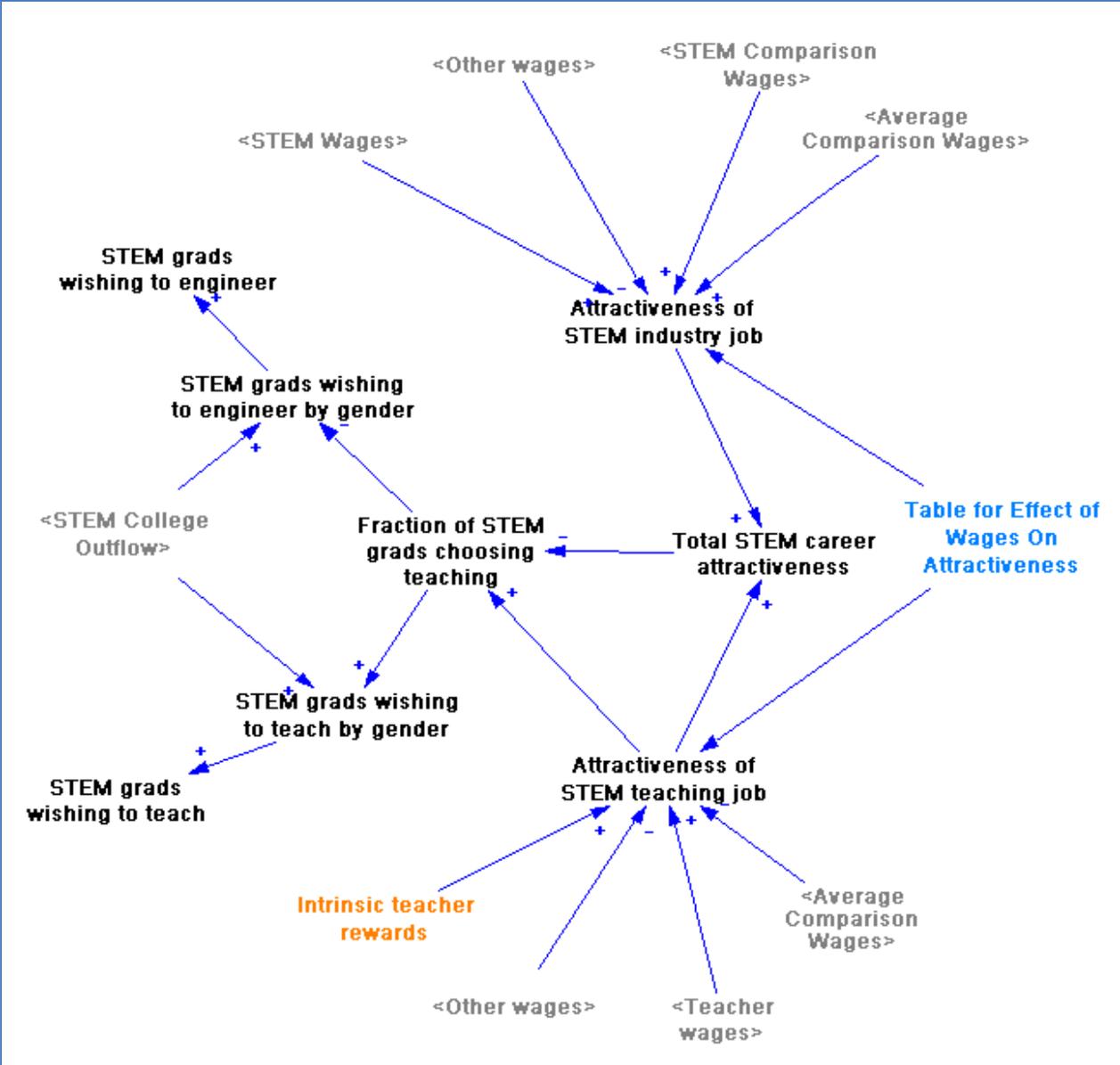


Figure 86: Attractiveness of STEM Industry Work and STEM Teaching

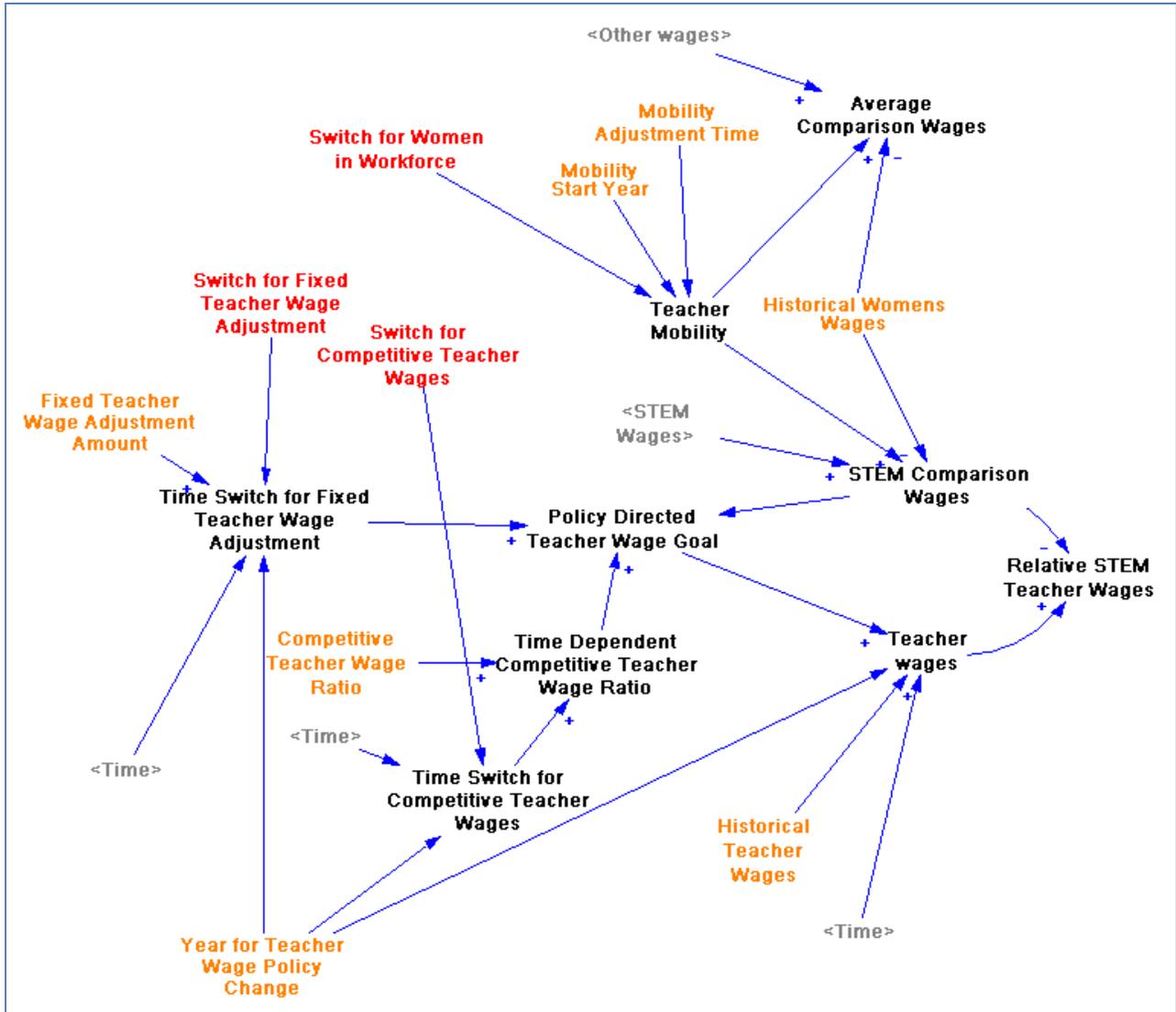


Figure 87: Teacher Wages and Policy Testing

Appendix D: Model Equations

Becoming Children[gender]=
 birthing/2
 Units: student/Year

Duration Elementary=
 6
 Units: Year

Birth Rate=
 IF THEN ELSE(Switch for Birth Rate
 Type, Variable Birth Rate , Constant Birth Rate
)
 Units: person/Year

Duration HS=
 4
 Units: Year

birthing=
 Birth Rate
 Units: person/Year

Duration JH=
 3
 Units: Year

College Fraction That Continue STEM[gender]=
 0.5
 Units: 1

Duration Pre School=
 5
 Units: Year

College Fraction That Do Not Continue
 STEM[gender]=
 1-College Fraction That Continue
 STEM[gender]
 Units: 1

dying=
 Population/Life Span
 Units: person/Year

Combined STEM College Outflow=
 SUM(STEM College Outflow[gender!])
 Units: people/Year

Enter Kindergarten=
 SUM(Entrance[gender!])
 Units: student/Year

Constant Birth Rate=
 IV Population*Fractional Death Rate
 Units: person/Year

Entrance[gender]= DELAY FIXED (
 Becoming Children[gender] , Duration
 Pre School, Pre School[gender]/Duration Pre
 School
)
 Units: student/Year

Duration College=
 4
 Units: Year

fertility=
 1.5/70
 Units: person/(Year * person)

Fractional Death Rate=

1/70
Units: 1/Year

Graduation Elementary[gender]= DELAY FIXED (Entrance[gender]*Fraction That Continue STEM[gender], Duration Elementary, STEM Students Elementary[gender]*Fraction That Continue STEM[gender] /Duration Elementary)
Units: student/Year

Graduation HS[gender]= DELAY FIXED (Graduation JH[gender]*Fraction That Continue STEM[gender], Duration HS , STEM Students HS [gender]*Fraction That Continue STEM[gender] /Duration HS)
Units: student/Year

Graduation JH[gender]= DELAY FIXED (Graduation Elementary[gender]*Fraction That Continue STEM[gender], Duration JH , STEM Students JH[gender]*Fraction That Continue STEM[gender] /Duration JH)
Units: student/Year

IV Population= INITIAL(3e+008)
Units: person

Leave STEM College[gender]= DELAY FIXED(Graduation HS[gender]*College Fraction That Do Not Continue STEM [gender], Duration College , STEM Students College[gender]*College Fraction That Do Not Continue STEM [gender]/Duration College)
Units: person/Year

Leave STEM Elementary[gender]= DELAY FIXED (Entrance[gender]*Fraction That Do Not Continue STEM[gender], Duration Elementary , STEM Students Elementary[gender]*Fraction That Do Not Continue STEM[gender]/Duration Elementary)
Units: student/Year

Leave STEM HS[gender]= DELAY FIXED (Graduation JH[gender]*Fraction That Do Not Continue STEM[gender], Duration HS , STEM Students HS[gender] *Fraction That Do Not Continue STEM[gender]/Duration HS)
Units: student/Year

Leave STEM JH[gender]= DELAY FIXED (Graduation Elementary[gender]*Fraction That Do Not Continue STEM[gender], Duration JH , STEM Students JH[gender] *Fraction That Do Not Continue STEM[gender] /Duration JH)
Units: student/Year

Life Span=
70
Units: Year

Pipeline Following Elementary=
SUM(Graduation Elementary[gender!])
Units: student/Year

Pipeline Following HS=
SUM(Graduation HS[gender!])
Units: student/Year

Pipeline Following JH=
SUM(Graduation JH[gender!])
Units: student/Year

Population= INTEG (
 birthing-dying,
 IV Population)

Units: person

Pre School[gender]= INTEG (
 -Becoming
 Children[gender]+Entrance[gender],
 IV Pre School[gender])

Units: student

STEM College Graduation=
 SUM(STEM College Outflow[gender!])

Units: student/Year

STEM College Outflow[gender]=
 DELAY FIXED(Graduation
 HS[gender]*College Fraction That Continue
 STEM[gender
], Duration College , STEM Students
 College[gender]*College Fraction That Continue
 STEM
 [gender]/Duration College)

Units: person/Year

STEM Students College[gender]= INTEG (
 Graduation HS[gender]-Leave STEM
 College[gender]-STEM College Outflow[gender
],

IV STEM Students

College[gender])

Units: person

STEM Students Elementary[gender]= INTEG (
 Entrance[gender]-Graduation
 Elementary[gender]-Leave STEM
 Elementary[gender
],

IV STEM Students

Elementary[gender])

Units: student

STEM Students HS[gender]= INTEG (
 -Graduation HS[gender]+Graduation
 JH[gender]-Leave STEM HS[gender],
 IV STEM Students HS[gender])

Units: student

STEM Students JH[gender]= INTEG (
 Graduation Elementary[gender]-
 Graduation JH[gender]-Leave STEM JH[gender],
 IV STEM Students JH[gender])

Units: student

Switch for Birth Rate Type=

0

Units: 1 [0,1,1]

Variable Birth Rate=
 fertility*Population

Units: person/Year

Adjustment Teacher Hires=
 Qualified STEM Teacher
 Shortfall/Time to close STEM teacher hiring gap

Units: teacher/Year

Desired Teacher Hires=
 MAX(0, Adjustment Teacher
 Hires+Teachers Leaving)

Units: teacher/Year

Duration of Career=

40

Units: Year

Expected Relative STEM Teacher Wages=
 IF THEN ELSE(Switch for quality
 variation among STEM educated teachers,
 LOOKUP INVERT
 (Table for Effect of Teacher Wages on New
 Teacher Quality, Average Quality of STEM
 Educated Teachers
), 1)

Units: fraction

Must use switch here because a floating point overflow error occurs in the LOOKUP INVERT if we don't guard it in this case.

Fractional Teacher Attrition Rate=
 IF THEN ELSE(Switch for Quality Compensation Correlation :AND: Time >= Year for Teacher Wage Policy Change , 1.122,Teacher Attrition Rate Modifier From Wage Expectation Changes)/Normal Average STEM Teaching Career Length
 Units: 1/Year

IV STEM Workers= INITIAL(
 (STEM grads wishing to engineer+STEM teacher grads without teaching jobs)* Duration of Career)
 Units: person

New Engineers Entering Workforce=
 STEM grads wishing to engineer+STEM teacher grads without teaching jobs
 Units: worker/Year

New STEM Teacher Hiring=
 MIN(Desired Teacher Hires, STEM grads wishing to teach)
 Units: teacher/Year

Normal Average STEM Teaching Career Length=
 10
 Units: Year

Qualified STEM Teacher Shortfall=
 STEM Teachers Needed-STEM Educated Teachers
 Units: person

STEM Educated Teachers= INTEG (

New STEM Teacher Hiring-Teacher Attrition-Teacher Retirement, IV STEM Teachers)
 Units: teacher

STEM Retirement=
 STEM Workers/Duration of Career
 Units: worker/Year

STEM teacher grads without teaching jobs=
 MAX(0, STEM grads wishing to teach- Desired Teacher Hires)
 Units: people/Year

STEM Teachers Needed=
 (SUM(STEM Students Elementary[gender!])+SUM(STEM Students JH[gender!])+SUM (STEM Students HS[gender!]))/Student Teacher Ratio Goal
 Units: person

STEM Workers= INTEG (
 New Engineers Entering Workforce+Teacher Attrition-STEM Retirement, STEM Positions)
 Units: worker

Student Teacher Ratio Goal=
 50
 Units: 1

Switch for Quality Compensation Correlation=
 0
 Units: 1 [0,1,1]

Switch for Teacher Attrition=
 1
 Units: 1 [0,1,1]
 Can teachers quit and become STEM workers?

Teacher Attrition=

STEM Educated Teachers*Fractional
 Teacher Attrition Rate*Switch for Teacher
 Attrition
 *Teacher Mobility
 Units: teacher/Year

Teacher Attrition Rate Modifier From Wage
 Expectation Changes=
 IF THEN ELSE(Switch for quality
 variation among STEM educated
 teachers,Expected Relative STEM Teacher
 Wages
 /Relative STEM Teacher Wages, 1)
 Units: Dimensionless
 Must use switch here so that attrition rates are
 not modified
 based on quality variation when
 we don't intend quality
 variation to have any impact.

Teacher Retirement=
 STEM Educated Teachers/Duration of
 Career
 Units: teacher/Year

Teachers Leaving=
 Teacher Attrition+Teacher Retirement
 Units: teacher/Year

Time to close STEM teacher hiring gap=
 1
 Units: Year
 Effect of Labor Gap on Pay=
 IF THEN ELSE(Pay Curve
 Switch,Table for effect of Labor Gap on
 Pay(Relative STEM Labor Gap
), Table for effect of Labor Gap on Pay
 2(Relative STEM Labor Gap))
 Units: 1

Effect of STEM Wages on Number of Positions=

IF THEN ELSE(Job Curve Switch, Table
 for effect of STEM Wages on Number of
 Positions
 (Relative STEM wages), Table for effect of STEM
 Wages on Number of Positions 2
 (Relative STEM wages))
 Units: 1

Indicated STEM Positions=
 Effect of STEM Wages on Number of
 Positions*Societal Demand for STEM Work
 Units: job

Indicated STEM Wages=
 Effect of Labor Gap on Pay*STEM
 Wages
 Units: dollar/worker

IV STEM Positions Constant=
 7.207e+006
 Units: job

IV STEM Wages=
 LOOKUP INVERT(Table for effect of
 wages on retention, Normal Initial Fraction That
 Continue STEM
)
 Units: dollar/person

IV STEM Wages Constant=
 0.9297
 Units: dollar/worker [0.8,1.2,0.001]
 This parameter is tuned by hand to set initial
 wages of STEM
 workers to start the system in
 equilibrium.

job creation=
 MAX(0, STEM Position Gap/Job Creation
 Smoothing Time)
 Units: job/Year

Job Creation Smoothing Time=

1

Units: Year

$0.02 + \text{STEP}(0.2, 1990)$

Units: job/person

Job Curve Switch=

0

Units: Dimensionless [0,1,1]

Which curve to use?

Population Fraction of STEM Postions FLAT=

0.02

Units: job/person

job destruction=

$\text{MAX}(0, -\text{STEM Position Gap}/\text{Job}$

Destruction Smoothing Time)

Units: job/Year

Relative STEM Labor Gap=

$\text{XIDZ}(\text{STEM Positions}, \text{STEM}$

Workers, $1e+012$)

Units: job/worker

Job Destruction Smoothing Time=

1

Units: Year

Relative STEM wages=

$\text{STEM Wages}/\text{Other wages}$

Units: 1

Other wages=

1

Units: dollar/worker

Societal Demand for STEM Work=

$\text{Population} * \text{Population Fraction of}$

STEM Positions

Units: job

Pay Curve Switch=

0

Units: Dimensionless [0,1,1]

Which curve to use?

STEM Position Gap=

$\text{Indicated STEM Positions} - \text{STEM}$

Positions

Units: job

Population Fraction of STEM Positions=

$\text{Population Fraction of STEM Positions}$

With RAMP

Units: job/person

STEM Position Growth=

0.02

Units: Dimensionless [0,0.2,0.01]

Does the amount of demand for STEM workers increase over time.

If so, by how much?

Population Fraction of STEM Positions With RAMP=

$0.02 + \text{RAMP}(\text{STEM Position Growth}/90, 1950, 2040) + (\text{Switch for business cycle oscillation} * 0.002 * \text{Input})$

Units: job/person

STEM Positions= INTEG (

$\text{job creation} - \text{job destruction},$

IV STEM Positions Constant)

Units: job

Population Fraction of STEM Positions With STEP=

STEM Wages= INTEG (

$\text{wage increase} - \text{wage decrease},$

IV STEM Wages Constant)

Units: dollar/worker

Switch for business cycle oscillation=
0

Units: Dimensionless [0,1,1]

Table for effect of Labor Gap on Pay(

[(0,0)-(10,100)],(-
0.00611621,0.0701754),(0.00611621,0.149123)
,(0.183486,0.219298
) ,(0.348624,0.236842),(0.550459,0.438596),(0.7
52294,0.587719),(0.88685,0.833333
) ,(1,1),(1.14985,1.17544),(1.37615,1.49123),(1.7
37,1.86842),(2.31193,2.68421
) ,(2.86239,3.75439),(3.3578,5.04386),(3.85321,
6.71053),(4.6789,9.25439),(6.02446
,13.8596),(7.30887,18.7719),(8.65443,25.9211),
(9.05199,30),(9.66361,40.3509
) ,(9.93884,53.5088))

Units: 1

Table for effect of Labor Gap on Pay 2(

[(0,0)-(100,100)],(-
0.0030581,0.236842),(0.103976,0.27193),(0.26
2997,0.333333
) ,(0.431193,0.403509),(0.593272,0.517544),(0.7
37003,0.662281),(0.88685,0.833333
) ,(1,1),(1.14985,1.29825),(1.23547,1.50877),(1.3
8226,1.82456),(1.65138,2.52632
) ,(2.22018,4.12281),(2.75229,5.5),(3.34862,6.80
702),(3.79205,7.89474),(4.8685
,11),(5.96942,14.8333),(7.30887,18.7719),(8.65
443,25.9211),(9.05199,30),(9.66361
,40.3509),(9.93884,53.5088))

Units: 1

Table for effect of STEM Wages on Number of
Positions(

[(0,0)-
(10,10)],(0.030581,10),(0.33945,2.86842),(0.422
018,2.40789),(0.477064
,2.15789),(0.550459,1.86842),(0.623853,1.6842
1),(0.706422,1.48684),(0.788991

,1.34211),(0.862385,1.21053),(0.926606,1.0921
1),(1,1),(1.07339,0.947368),(1.17431
,0.868421),(1.3211,0.815789),(1.54128,0.75),(1.
80734,0.684211),(2.00917,0.671053
) ,(2.13761,0.631579),(2.33945,0.605263),(2.577
98,0.552632),(2.6055,0.552632
) ,(2.77064,0.539474),(2.88073,0.526316),(2.935
78,0.526316),(3,0.5),(4,0.35)
) ,(5,0.2),(6,0.1))

Units: 1

Table for effect of STEM Wages on Number of
Positions 2(

[(0,0)-
(10,10)],(0.030581,10),(0.33945,2.86842),(0.422
018,2.59211),(0.486239
,2.35526),(0.550459,2.17105),(0.636086,1.8947
4),(0.703364,1.71053),(0.801223
,1.5),(0.862385,1.333333),(0.929664,1.19298),(1,
1),(1.08257,0.842105),(1.19266
,0.736842),(1.33333,0.596491),(1.52905,0.4824
56),(1.80428,0.368421),(2.01835
,0.315789),(2.14679,0.315789),(2.34862,0.2894
74),(2.53211,0.25),(2.6422,0.236842
) ,(2.76147,0.223684),(2.87156,0.210526),(2.981
65,0.210526),(3.19266,0.197368
) ,(3.96024,0.184211),(5.00917,0.131579),(6,0.1
)

Units: 1

wage decrease=

MAX(0, -1 * (Indicated STEM Wages-
STEM Wages)/Wage Decrease Smoothing Time
)

Units: dollars/person/Year

Wage Decrease Smoothing Time=

1

Units: Year

wage increase=

MAX(0, (Indicated STEM Wages-STEM Wages)/Wage Increase Smoothing Time)
Units: dollar/worker/Year

Wage Increase Smoothing Time=
1

Units: Year
Fraction That Are Able To Continue STEM=
Table for effect of teacher quality on retention(Average STEM Teacher Quality
)
Units: 1

Fraction That Continue STEM[gender]=
(Fraction That Are Able To Continue STEM*Fraction That Wish to Continue STEM)+Gender Related Continuation Modifier[gender]
Units: fraction

Fraction That Do Not Continue STEM[gender]=
1-Fraction That Continue STEM[gender]
Units: 1

Fraction That Wish to Continue STEM=
Table for effect of wages on retention(Relative STEM wages)
Units: 1

Gender Related Continuation Modifier[gender]=
0.1,0.1
Units: Dimensionless

Initial Fraction That Continue STEM[gender]=
Normal Initial Fraction That Continue STEM+Gender Related Continuation Modifier [gender]
Units: fraction [0,1,0.01]

Normal Initial Fraction That Continue STEM=
0.3519

Units: fraction [0,1,0.0001]
This parameter is tuned by hand to make the system start in equilibrium. It controls the number of students in all stages of the education pipeline.

Table for effect of teacher quality on retention([(-0.04,0)-(1000,1000)],(-0.030581,0.0394737),(0.122202,0.245614),(0.253211,0.407895),(0.402936,0.578947),(0.576514,0.72807),(0.718654,0.815789),(0.932722,0.868421),(1.23853,0.912281),(993.884,100))
Units: Dimensionless

Table for effect of teacher quality on retention Orig([(-0.04,0)-(2,1)],(-0.030581,0.1),(0.114128,0.307018),(0.252844,0.482456),(0.422385,0.622807),(0.576514,0.72807),(0.718654,0.815789),(0.932722,0.868421),(1.23853,0.912281),(993.884,5))
Units: Dimensionless

Table for effect of wages on retention([(0,0)-(10,1)],(0,0.025),(0.220183,0.0570175),(0.452599,0.118421),(0.678899,0.20614),(0.874618,0.346491),(1,0.5),(1.15596,0.605263),(1.3945,0.714912),(1.66972,0.798246),(1.87768,0.859649),(2.02446,0.881579),(100,1))
Units: 1

Attractiveness of STEM industry job[male]=
Table for Effect of Wages On Attractiveness(STEM Wages/Other wages)
Attractiveness of STEM industry job[female]=
Table for Effect of Wages On Attractiveness(STEM Comparison Wages/Average Comparison Wages)

)
 Units: Dmnl
 Attractiveness of STEM teaching job[male]=
 Table for Effect of Wages On
 Attractiveness(Teacher wages/Other wages)
 Attractiveness of STEM teaching job[female]=
 Table for Effect of Wages On
 Attractiveness(Teacher wages/Average
 Comparison Wages
)
 Units: Dmnl

Fraction of STEM grads choosing
 teaching[gender]=
 Attractiveness of STEM teaching
 job[gender]/Total STEM career attractiveness
 [gender]
 Units: Dmnl

STEM grads wishing to engineer=
 SUM(STEM grads wishing to engineer
 by gender[gender!])
 Units: people/Year

STEM grads wishing to engineer by
 gender[gender]=
 (1-Fraction of STEM grads choosing
 teaching[gender])*STEM College Outflow[
 male]
 Units: people/Year

STEM grads wishing to teach=
 SUM(STEM grads wishing to teach by
 gender[gender!])
 Units: people/Year

STEM grads wishing to teach by
 gender[gender]=
 Fraction of STEM grads choosing
 teaching[gender]*STEM College
 Outflow[gender]

] Units: people/Year
 Table for Effect of Wages On Attractiveness(
 [(0,0)-
 (1.2,1)],(0,0),(0.165138,0.0131579),(0.281346,0.
 0263158),(0.397554,
 0.0438596),(0.458716,0.0482456),(0.517431,0.
 0614035),(0.568807,0.0745614),(
 0.631193,0.0833333),(0.678899,0.0877193),(0.
 755963,0.110526),(0.829358,0.150439
),(0.895413,0.193421),(0.954128,0.254386),(0.9
 96942,0.289474),(1.04587,0.333333
),(1.11315,0.394737),(1.14985,0.451754),(1.198
 78,0.526316),(1.25994,0.587719
),(1.30275,0.649123),(1.33333,0.710526),(1.388
 38,0.754386),(1.43119,0.789474
),(1.47401,0.833333),(1.51682,0.877193),(1.565
 75,0.921053),(1.61468,0.95614
),(1.65138,0.964912),(1.69419,0.973684),(1.749
 24,0.969298),(1.82263,0.986842
),(9.93884,1.97368))
 Units: Dmnl

Table for Effect of Wages On Attractiveness
 Orig(
 [(0,0)-
 (2,2)],(0,0),(0.165138,0.0131579),(0.281346,0.0
 263158),(0.397554,0.0438596
),(0.489297,0.0789474),(0.556575,0.0964912),(
 0.574924,0.0964912),(0.666667,
 0.114035),(0.75841,0.140351),(0.83792,0.1754
 39),(0.899083,0.22807),(0.954128
),0.254386),(0.996942,0.289474),(1.04587,0.333
 333),(1.11315,0.394737),(1.14985
),0.451754),(1.19878,0.526316),(1.25994,0.5877
 19),(1.30275,0.649123),(1.33333
),0.710526),(1.38838,0.754386),(1.43119,0.7894
 74),(1.47401,0.833333),(1.51682
),0.877193),(1.56575,0.921053),(1.61468,0.9561
 4),(1.65138,0.964912),(1.69419

,0.973684),(1.74924,0.969298),(1.82263,0.986842),(9.93884,1.97368))
 Units: Dmnl

Total STEM career attractiveness[gender]=
 Attractiveness of STEM industry
 job[gender]+Attractiveness of STEM teaching
 job
 [gender]
 Units: Dmnl
 IV Pre School[gender]= INITIAL(
 birthing*Duration Pre School/2)
 Units: student

IV STEM Positions= INITIAL(
 IV Population*Population Fraction of
 STEM Positions)
 Units: person

IV STEM Students College[gender]= INITIAL(
 IV STEM Students HS[gender]/Duration
 HS*Duration College*Fraction That Continue
 STEM
 [gender])
 Units: student

IV STEM Students Elementary[gender]= INITIAL(
 (IV Pre School[gender]/Duration Pre
 School)*Duration Elementary)
 Units: student

IV STEM Students HS[gender]=
 (IV STEM Students JH[gender]/Duration
 JH)*Duration HS*Initial Fraction That Continue
 STEM
 [gender]
 Units: student

IV STEM Students JH[gender]= INITIAL(
 (IV STEM Students
 Elementary[gender]/Duration

Elementary)*Duration JH*Initial Fraction That
 Continue STEM
 [gender])
 Units: student

IV STEM Teachers= INITIAL(
 STEM Teachers Needed)
 Units: teacher
 Average Comparison Wages=
 Historical Womens
 Wages+(Teacher Mobility*(Other wages-
 Historical Womens Wages
))
 Units: dollars/person

Competitive Teacher Wage Ratio=
 1
 Units: Dimensionless [0.1,3,0.1]
 If teachers are paid wages proportional to STEM
 workers, what
 percentage of STEM worker pay
 are they receiving? If this number
 is set to 1, then they are paid
 equally.

Fixed Teacher Wage Adjustment Amount=
 0
 Units: dollars/teacher [0,3,0.1]
 If teachers are given a fixed wage increase,
 what is the new
 wage level?

Historical Teacher Wages= INITIAL(
 0.6)
 Units: dollar/teacher

Historical Womens Wages=
 0.4
 Units: dollar/person

Intrinsic teacher rewards[gender]=
 0.1

Units: dollars/teacher

Mobility Adjustment Time=

10

Units: Year [1,50,1]

If women are allowed to enter the workforce,
how long does this
transition take?

Mobility Start Year=

1975

Units: Year [1940,2400,1]

If women are allowed to enter the workforce,
what year does this
transition start?

Policy Directed Teacher Wage Goal=

(STEM Comparison Wages*Time

Dependent Competitive Teacher Wage

Ratio)+Time Switch for Fixed Teacher Wage

Adjustment

Units: dollar/teacher

Relative STEM Teacher Wages=

ZIDZ(Teacher wages,STEM Comparison

Wages)

Units: fraction

STEM Comparison Wages=

Historical Womens Wages+(Teacher

Mobility*(STEM Wages-Historical Womens

Wages

))

Units: dollars/teacher

Switch for Competitive Teacher Wages=

0

Units: Dimensionless [0,1,1]

After the current year, are teachers paid wages
that are tied to
the amount paid to STEM
workers?

Switch for Fixed Teacher Wage Adjustment=

0

Units: Dimensionless [0,1,1]

After the current year are STEM teachers given
a fixed wage
going forward that is higher
than before?

Switch for Women in Workforce=

0

Units: 1 [0,1,1]

Are women allowed to enter the workforce?

Teacher Mobility=

RAMP(1/Mobility Adjustment Time,

Mobility Start Year , Mobility Start Year

+ Mobility Adjustment Time) *Switch for

Women in Workforce

Units: 1

Teacher wages=

IF THEN ELSE(Time >= Year for Teacher

Wage Policy Change, MAX(Policy Directed

Teacher Wage Goal

, Historical Teacher Wages

) , Historical Teacher Wages)+Intrinsic

teacher rewards[female]

Units: dollar/teacher

Time Dependent Competitive Teacher Wage

Ratio=

Competitive Teacher Wage Ratio*Time

Switch for Competitive Teacher Wages

Units: Dimensionless

Time Switch for Competitive Teacher Wages=

IF THEN ELSE(Time >= Year for Teacher

Wage Policy Change, Switch for Competitive

Teacher Wages

, 0)

Units: 1

Time Switch for Fixed Teacher Wage Adjustment=
 IF THEN ELSE(Time >= Year for Teacher Wage Policy Change, Switch for Fixed Teacher Wage Adjustment
 *Fixed Teacher Wage Adjustment Amount, 0)
 Units: dollar/teacher

Year for Teacher Wage Policy Change=
 2008
 Units: Year [1940,2400,1]
 In what year does a new wage policy begin? (2008 by default)
 Average Quality of New STEM Educated Teachers=
 IF THEN ELSE(Switch for quality variation among STEM educated teachers, Table for Effect of Teacher Wages on New Teacher Quality
 (Relative STEM Teacher Wages),
 IV Average Quality of STEM Educated Teachers)
 Units: quality/teacher

Average Quality of STEM Educated Teachers=
 ZIDZ(Total Effective STEM Educated Teacher Quality,STEM Educated Teachers)
 Units: quality/teacher

Average STEM Teacher Quality=
 IF THEN ELSE(Switch for impact of STEM educated teacher shortage, (Average Quality of STEM Educated Teachers
 *Percentage Classrooms Taught By STEM Educated Teachers)+(Quality of Unqualified Teachers
 *(1-Percentage Classrooms Taught By STEM Educated Teachers)), Average Quality of STEM Educated Teachers)
 Units: quality/teacher

Increase in Quality from Hiring=
 Average Quality of New STEM Educated Teachers*New STEM Teacher Hiring
 Units: quality/Year

IV Average Quality of STEM Educated Teachers= INITIAL(
 Table for Effect of Teacher Wages on New Teacher Quality
 (Relative STEM Teacher Wages))
 Units: quality/teacher

IV Total Effective STEM Educated Teacher Quality=
 IV Average Quality of STEM Educated Teachers*IV STEM Teachers
 Units: quality

Loss of Quality from Attrition=
 Average Quality of STEM Educated Teachers*Teachers Leaving
 Units: quality/Year

Percentage Classrooms Taught By STEM Educated Teachers=
 STEM Educated Teachers/STEM Teachers Needed
 Units: fraction

Quality of Unqualified Teachers=
 0.1
 Units: quality/teacher [0,1,0.01]
 What is the quality level of teachers who are teaching STEM subjects, but are not trained in STEM?

Switch for impact of STEM educated teacher shortage=
 1
 Units: Dimensionless [0,1,1]

Does a shortage in the number of qualified
STEM teachers impact
teacher quality?

Switch for quality variation among STEM
educated teachers=

1

Units: Dimensionless [0,1,1]

Does quality variation among teacherw who
have STEM credentials
occur?

Table for Effect of Teacher Wages on New
Teacher Quality(
[(0,0)-

(3,1)],(0.00917431,0.236842),(0.155963,0.2543
86),(0.302752,0.276316
,(0.422018,0.315789),(0.550459,0.355263),(0.6
69725,0.403509),(0.779817,0.460526
,(0.889908,0.530702),(1,0.592105),(1.10092,0.
653509),(1.22018,0.723684),(1.34862
,0.776316),(1.50459,0.850877),(1.61468,0.8771
93),(1.6789,0.885965),(1.77982
,0.912281),(1.93578,0.938596),(2.13761,0.9473
68),(2.33945,0.960526),(2.57798
,0.973684),(2.79817,0.986842),(2.98165,1))

Units: quality/teacher

Table for Effect of Teacher Wages on New
Teacher Quality Orig(
[(0,0)-

(3,1)],(0.00917431,0.00877193),(0.211009,0.03
94737),(0.348624,0.0614035
,(0.477064,0.105263),(0.587156,0.157895),(0.7
15596,0.22807),(0.798165,0.315789
,(0.899083,0.403509),(1,0.5),(1.11009,0.59210
5),(1.22936,0.684211),(1.34862
,0.776316),(1.50459,0.850877),(1.61468,0.8771
93),(1.6789,0.885965),(1.77982
,0.912281),(1.93578,0.938596),(2.13761,0.9473
68),(2.33945,0.960526),(2.57798
,0.973684),(2.79817,0.986842),(2.98165,1))

Units: quality/teacher

Total Effective STEM Educated Teacher Quality=
INTEG (

Increase in Quality from Hiring-Loss of
Quality from Attrition,

IV Total Effective STEM
Educated Teacher Quality)

Units: quality

Unqualified STEM Teachers=

MAX(0, Qualified STEM Teacher
Shortfall)

Units: teacher

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