America Disrupted: Dynamics of the Technical Capability Crisis

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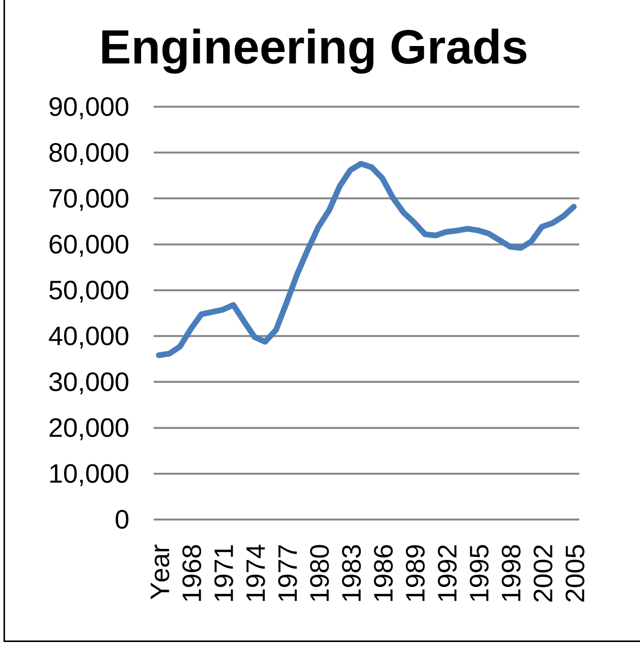
Abstract: This study investigates the causes of the nearly twenty-five year decline in the percentage of U.S. born undergraduates earning degrees in engineering. This dramatic decline has occurred despite incredibly high pay and low unemployment among individuals holding engineering degrees. On the surface the 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. The 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.

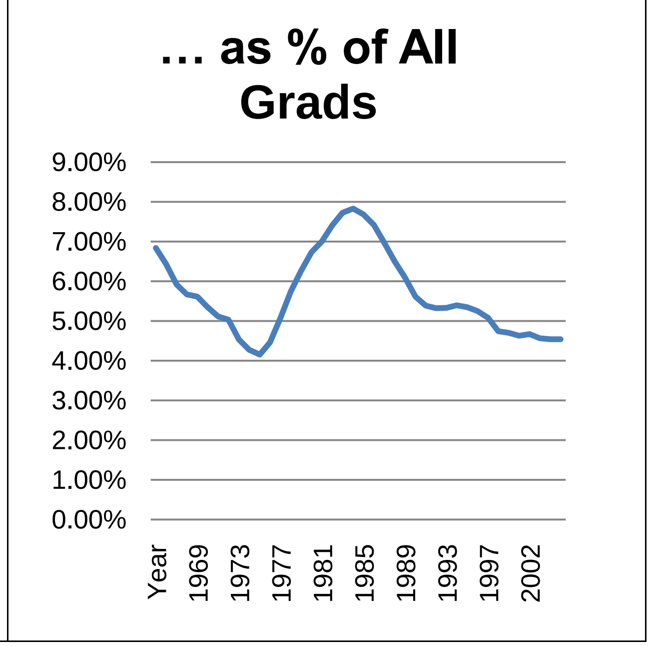
This work presents a theory (and supporting data) that high industry pay for STEM workers and low pay for STEM K-12 teachers directly cause long-term labor shortages that are self perpetuating. The fact that mathematics knowledge is highly sequential with strong dependencies on past-performance exacerbates the situation. Societal shifts that occurred in the 1950's through the 1980's could have resulted in the perplexing behavior seen from 1985 until the present day. Policy proposals are simulated in the model to test their ability to move the system in a more positive direction. The system exhibits "tipping point" behavior. Small reforms will have negligible impact while significant reforms have the potential to make the system move into a fundamentally better pattern of behavior, but only after considerable delays.

Keywords: *STEM Education, Engineering Education, K-12 Education, Public Policy, System Dynamics, STEM Workforce, Disruption.*

Introduction

This report investigates the cause of the nearly twenty-five year decline in the percentage of U.S. born undergraduates earning degrees in engineering. As shown in the following figures, the percentage of undergraduates earning degrees in engineering fields peaked in the year 1985 at 7.83%. It has declined most years since 1985 and is now at 4.54%. (National Science Foundation WebCASPAR System n.d.). 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.





This work was initiated at the request of the Boeing Corporation in response to a concern about its future technical workforce. A majority 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 believe their situation not to be unique. Similar concerns plague many U.S. based engineering and information technology firms. The current situation may represent a "tragedy of the commons" (Hardin 1968) that cannot be addressed by companies individually.

The subjects explored here have profound implications not only for high-tech firms, but for the continued prosperity of the United States. 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"* (NAS 2007, 29), "scientists and engineers tend, through innovation, to create new jobs not only for themselves but also for workers throughout the economy." Engineers and scientists not only create value for themselves and their firms, but they also tend to generate growth for others as a result of their economic activity. This is because unlike some other high-paying professions such as finance or law, 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.

While many are aware that persistent problems plague the United States' ability to produce a healthy indigenous technical workforce, and millions of dollars are spent attempting to help the situation, very few comprehensive systems approaches to solving the problem have been considered. This may in part be due to the fact that most explanations people give as the causes of these problems have an exogenous and linear nature. Many also heavily rely on fundamental attribution errors in which blame is explicitly assigned to children rather than the endogenous forces they experience. To illustrate this point, over 50 ordinary people were asked their opinion on why students do not study a subject that is so lucrative, and why such a dramatic decline has occurred between 1985 and today. Opinions that were commonly given include ideas that today's children are lazier for some reason or parents or more permissive. Another common misperception is that more money can be made in fields such as business, law, medicine, etc. It is important to question whether any of the common explanations could really have caused this decline.

Research Goals and Strategy

Model building focused on causal relationships affecting the number of engineers in the U.S. with the goal of finding high-leverage policies to improve the current situation. The model endogenously represents 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.

The strategy used to guide model creation and exploration involved iteratively collecting information from literature and subject matter experts. The model was developed through several stages of refinement as new knowledge was added to its structure. Insights about the system derived from model simulation were used to plan further information collection, development, and experimentation.

Model development and exploration was guided by three primary goals:

- ***Reproduce history****:* Endogenously reproduce the simultaneous long term strength of engineering wages and long term decline in U.S. born engineering graduates. Demonstrate a qualitative similarity between what has actually happened and the behavior produced by the model from 1940 until today. Justify all structural relationships in the model with relevant supporting literature so that the results are believable.
- ***Project history into the future****:* Use the models to better understand what the future might hold for the strength of the U.S. technical workforce if current policy is maintained. Project historical runs thirty years into the future (until 2040) to indicate where the system is likely to do under the current set of policies.
- ***Test alternative futures:*** Use historical runs as a starting point. Historical behavior will continue until 2008 when policy changes will be introduced. Attempt to determine if they will be effective if applied in the real world. Differences shown between the forward-looking "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.

The Model

Throughout this work, conceptual models will be presented that convey the meaning of the full version of the model. The simulating version of the model was built in *Vensim* and is available if the reader wishes to inspect its formulation and behavior. It contains three notional parts at the highest level:

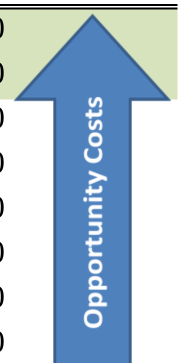
a. Supply and demand feedback loops showing how the career opportunities available to STEM workers affect the decision of currently enrolled students to maintain interest in STEM education and ultimately pursue a STEM career themselves.
b. A STEM education pipeline representing the number of students who continue to incrementally build mathematics competence at different stages of education.
c. 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.

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. Surprisingly to some, STEM degrees are worth more on average in both the short- and long-term than degrees in business and management. (NCES 2008).

Salaries of full-time employees by degree type and number of years since degree earned

	1-2 years	4-5 years	9-10 years
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/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



In addition to significant financial reward, high-skilled technical work offers career potential, opportunities for creativity, and other attractive life-style amenities. The same study found that engineers and computer scientists hold the highest level of belief that their current job has "career potential." STEM degree earners also held these beliefs more strongly than others. These careers provide remarkable stability as well. The NSF reported that unemployment among scientists and engineers in 2006 was 2.5%. (Kannankutty 2008) Very low unemployment is typical.

Engineering wages have risen relative to other wages in the economy in the past 100 years as the value of information and knowledge increased. For instance, wages of engineers relative to manufacturing employees grew significantly during the mid-twentieth century (Herrnstein and Murray 1996, 93). The value of information embedded in products as a proportion of total product cost continues to rise. Since 1970, engineers have earned between three to four times the U.S. median wage. (Scientific Manpower Commission 1967 - current) It should be noted that this data only includes averages for the profession, not the type of degree earned. 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.

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 disparity between impending retirements and indigenous replacements has been described by the National Academies as a "Gathering Storm" (NAS 2007) that may sap America's strength in those fields.

Data cited in the next few sections were extracted from the NSF WebCASPAR system. (National Science Foundation WebCASPAR System n.d.) Census data is from the U.S. Census Bureau web site from various current and archival population estimates. (U.S. Census Bureau Population Estimates n.d.)

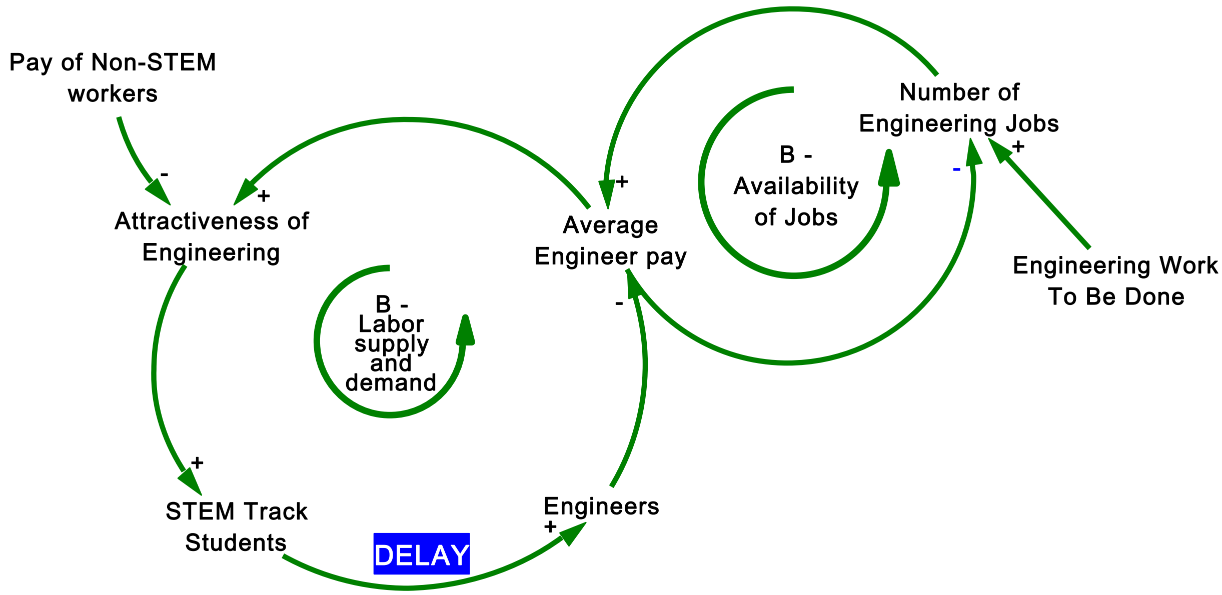
Between 1965 and today, the number of people earning college degrees has tripled from 500,000 to 1,500,000. Over the course of this time period, the percentage of the population earning undergraduate degrees grew from 20% to 35%. However, this fast growth has not penetrated the engineering profession. The number of degrees awarded in engineering rose from 36,000 in 1965 to 78,000 in 1985. It then dropped until it hit a minimum of 59,000 in 2001 and then started to rise again. 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%. (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. The percentage of all college age people earning engineering degrees has been trending downward since the mid 1980's as well.

International Comparison

France and Finland now have twice as many engineering and natural sciences graduations per-capita as the U.S., while the U.S. has rates similar to Kyrgystan (NAS 2007, 100). While 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. Fifty five percent of engineering doctoral students in the U.S. are now foreign born. (NAS 2007, 35)

First Conceptual Model: Invisible Hand Loops

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:



The first loop in this picture represents an economic "Invisible Hand" regulating the number of people choosing to enter engineering. 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 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.

A second loop has been added to the model to reflect the fact that as wages go up, employers provide fewer jobs as they find substitutes or cut back on goals. Likewise, if wages in a profession decrease, employers will create more jobs because of the new profit potential. Supply and demand curves 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 loops and the impacts of other structure such as collective bargaining agreements or cartel-like behavior. The market for engineering talent is relatively unhindered. Because this market does not appear to be functioning correctly however, we must continue exploring additional structure that could bring about pathological behavior.

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.

The *Rising Above the Gathering Storm* report states that:

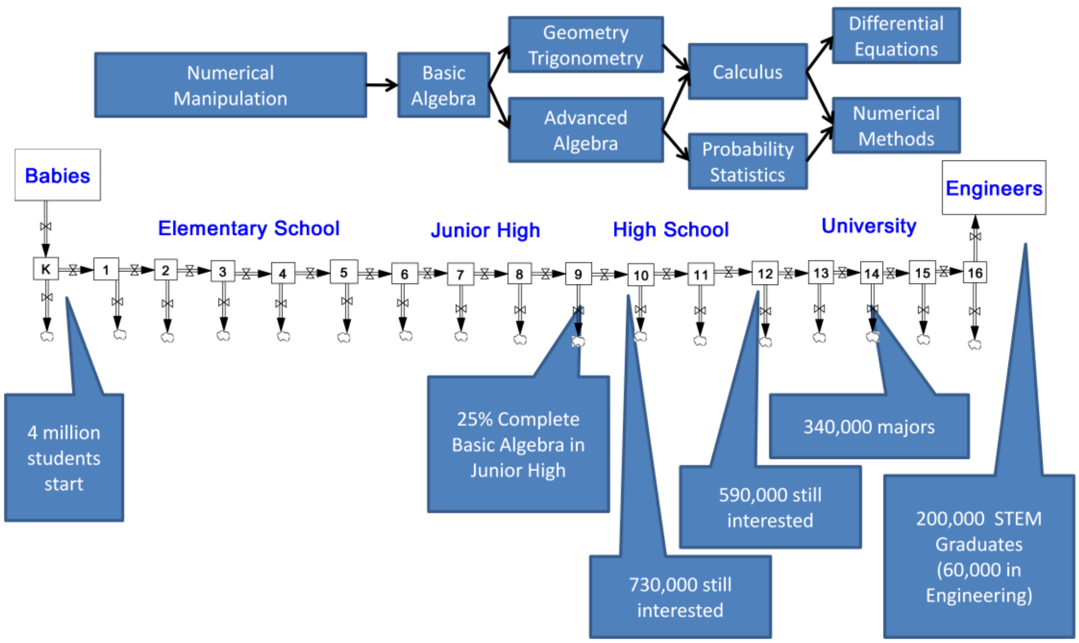
> “Student interest in research careers is dampened by several factors. First, there are important prerequisites for science and engineering study. Students who choose not to or are unable to finish algebra 1 before 9th-grade— which is needed for them to proceed in high school to geometry, algebra 2, 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.” (NAS 2007, 102)

The fact that ability to enter a profession requiring advanced mathematical training is dependent upon decisions made in the 8^{th} grade or earlier has important implications. Students who stopped studying mathematics at any point in their educational career almost never entered engineering because the entry barriers were too high. All educators interviewed over the course of this investigation agreed with the validity of this assessment. Many argued that the decision points came 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 serious point of discussion raised by some educators was to question whether this was an innate feature in mathematical knowledge, or whether it resulted from the way mathematics education is 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.

Second Conceptual Model: The STEM Gauntlet

As discussed previously, the unique nature of mathematics education makes it extremely hard to return once a student stops keeping up in mathematics. Therefore, the next conceptual 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 (NAS 2007, 115), and therefore have lower barriers to reentry. The STEM pipeline structure is therefore re-designated as the "STEM Gauntlet" in reference to the concept of "*running the gauntlet*." 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 calibrate our model, studies were found which reported student interest in STEM and rates of progression or falloff at different grade levels. This gave a 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, Hurtig and Farbrother 2003) The level of students still interested in STEM careers at various stages of the gauntlet (shown below) is drawn from that paper. ***One of the most devastating things Grismore tells us is that 82% of students fall out of the pipeline sometime prior to leaving junior high school.***



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 possible. 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.

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. We now examine other factors that may influence the retention rate of the STEM pipeline.

Student Performance Judged Internationally

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.

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
Czeck Republic	469	France	466
Germany	465	Czeck Republic	451
United States	442	Austria	435
Austria	436	United States	423

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 TIMMS Web site n.d.)

TIMSS measures performance at the fourth, eighth, and twelfth grade levels. 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 previous table shows the average TIMSS scores of students from different countries (NAS 2007, 132).

After results of this test were released, the U.S. Department of Education released a number of statements that can be found online. (Archived US Dept. Education TIMMS Responses n.d.). One such 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 is not a case of high-achievement among some and poor achievement among others. Rather, “the entire distribution of U.S. scores is shifted downward from that of many of the high performing countries.”

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 and Thum 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 and Thum 2004) Hanuschek 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.” (E. A. Hanushek n.d.) 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, Hanuschek 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, Hanuschek and Kain 2005) Teacher quality is a higher leverage point than student-teacher ratio, per-pupil spending, or any other school-related lever.

What Is Teacher Quality?

Given the primary importance of teacher quality on student outcomes, it is logical to ask what teacher quality is and how it could be 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 the simplistic formulas to gauge performance or methods rooted in Taylorism are an insult to the educational mission. Many economists therefore simply risk tautology by defining teacher quality as that which causes a relative improvement in students' performance over time. Hanuschek 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 and Rivkin 2006) The work summarizes the current state of research attempting to determine the impact that teacher, school related, and socio-economic parameters have on student outcomes. As discussed previously, 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 low socio-economic status on student outcomes. These researchers have also 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 of 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.

Judging the Proxies for Teacher Quality

Some measurable teacher attributes have been found to correlate with teacher quality while others have not. Unless otherwise noted, the information cited in this section has been drawn from Hanushek and Rivkin. (Hanushek and Rivkin 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 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 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 and program standards can 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 such 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 "learning curve" relationship with quality in some (but not all) cases. (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 correlation with student outcomes.

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* reports that 67% of physics, 61% of chemistry, 69% of junior high mathematics, and 93% of junior high physical science classes are taught by teachers ***without*** a major certification in the subject. (NAS 2007, 115) There are therefore two separate kinds of secondary school teacher quality: that which makes someone a good educator, and that which makes someone qualified to teach the subject. It is likely that many students have a poor teacher who knows a STEM subject well or an exceptional history teacher attempting to teach physics. Neither will be effective.

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 and Rivkin 2006) (Hoxby and Leigh 2004) 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 and Guryan n.d.)

Rising Against The Gathering Storm notes that "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." (NAS 2007, 113)

Elementary School STEM Quality

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:

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

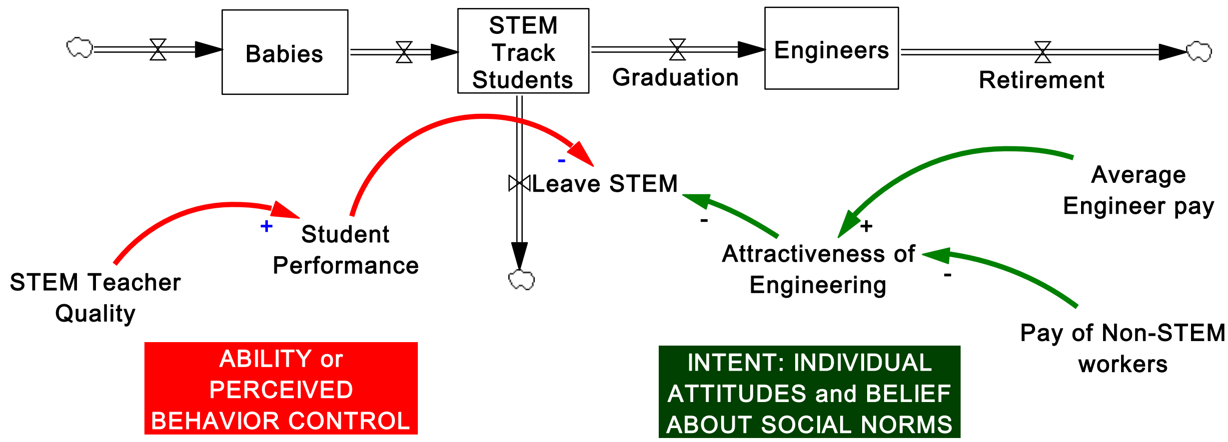
This numerical manipulation skill (essential to later performance in algebra) is supposed to be taught in the 4^{th} or 5^{th} grade. Furthermore, only 10% of those teachers could adequately explain what it meant conceptually to divide by a fraction or give a real-world example. (Ma 1999) (The same study 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 similar 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. 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, Hurtig and Farbrother 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.

Student Behavior: Where Ability Meets Intent

Although the "rational-actor" caricature presented so far is true if all else is held equal, other factors beyond future economic wealth clearly influence student behavior. Azjen's "Theory of Planned Behavior" (TPB) (Ajzen 1985) offers some guidance on how to proceed. This mathematical formulation from the field of social psychology attempts to tease apart and separately represent the factors that can influence behavior so that it is more predictable. At the highest level, it separates factors into beliefs about ability, individual attitudes, and beliefs about social norms. It structures multi-attribute utility equations inside matrices representing these determinants of behavioral intention. For instance, in survey results described in (Grismore, Hurtig and Farbrother 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 responding 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.



Teacher Quality Determinant: 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 chart previously used to show 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) Low teacher pay is an extremely plausible reason for low quality in the average K-12 educator.

In the 1940's both men and women could expect to earn significantly more than the average college graduate if they chose to enter a K-12 classroom (Hurley n.d.). Today, the financial penalty for teaching is 16% for females and 60% for males. However, this aggregate level data does not take into account pay differentiation by field. The opportunity cost of an engineer or computer scientist choosing to teach may be in the range of eighty to one hundred percent.

To illustrate this point, Marvin Minsky, a founder in the field of Artificial Intelligence, relayed a story 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.*

Teacher Quality Determinant: Gender Related Mobility

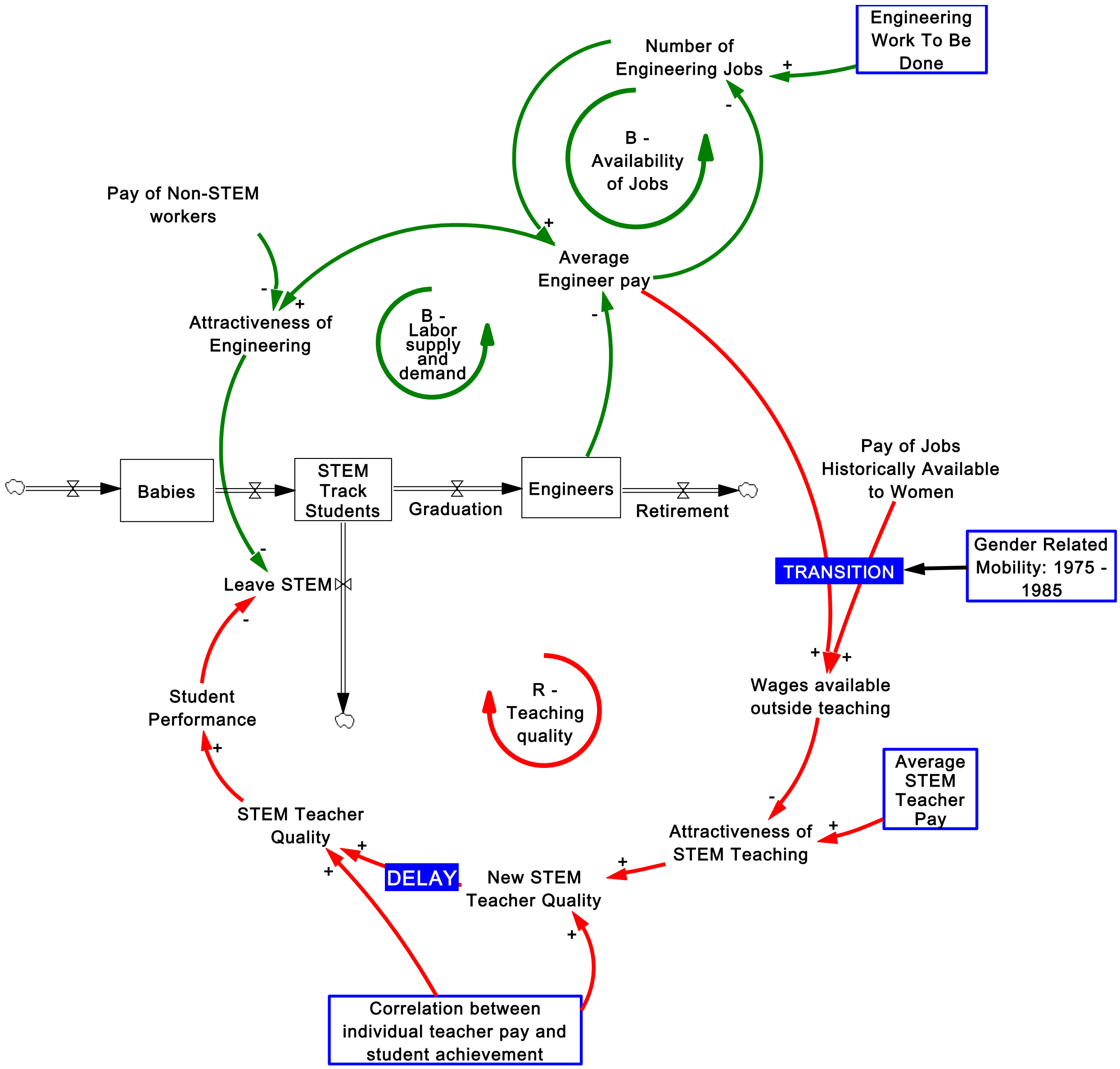
Another reason quality may have dropped over the course of this time is that liberalization of gender roles opened opportunities for college educated women beyond the more traditional choices of teaching, nursing, and social work. In the 1940's, 1950's, and 1960's the labor market for teachers operated somewhat independently of the labor market in industry. Because women were a trapped labor pool, teaching wages were compared against the wages of other jobs available to women when making career choices. (Temin 2002) In the 1940's, female teachers earned wages that were 15% higher than the average college educated woman. (Hurley n.d.) These female teachers went to college and entered the workforce at a time when many women did not. They may have been somewhat more progressive with high motivation and entrepreneurial tendencies. 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.

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 went to college due to gender role liberalization. During this transition period many 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 aspiring 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. (Kaufman and Hotchkiss 2006) The market for teachers began to clear based on quantity rather than quality. (Temin 2002) 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.

During period from 1975 to 1985 there was a massive influx of women earning Bachelor's degrees in engineering. Earlier, 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.

Economist Peter Temin says that "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…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." (Temin 2002)

Southwick and Indermit note that there has been a "decline in the quality of math and science teachers. They 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 and Indermit 1997)



Third 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. If engineer wages rise and STEM teaching pay remains stagnant, then the widening wage gap between industry and STEM teaching pay reduces the attractiveness of teaching jobs for people with strong STEM skills. (This loop is inactive until a transition period from 1975 to 1985.) This reduction in attractiveness causes a reduction in the quality level of the average person choosing STEM teaching as a profession and will eventually negatively impact the statistical distribution of teacher quality overall. A decline in average teacher quality will cause more students to stop considering STEM careers, not because they are uninterested in them (as shown previously), but because they believe themselves to be unqualified to continue. Most disturbingly, this eventually reduces the number of engineers further, causes engineering wages to rise again, and ultimately further widens the pay gap between STEM teacher and engineer.

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.

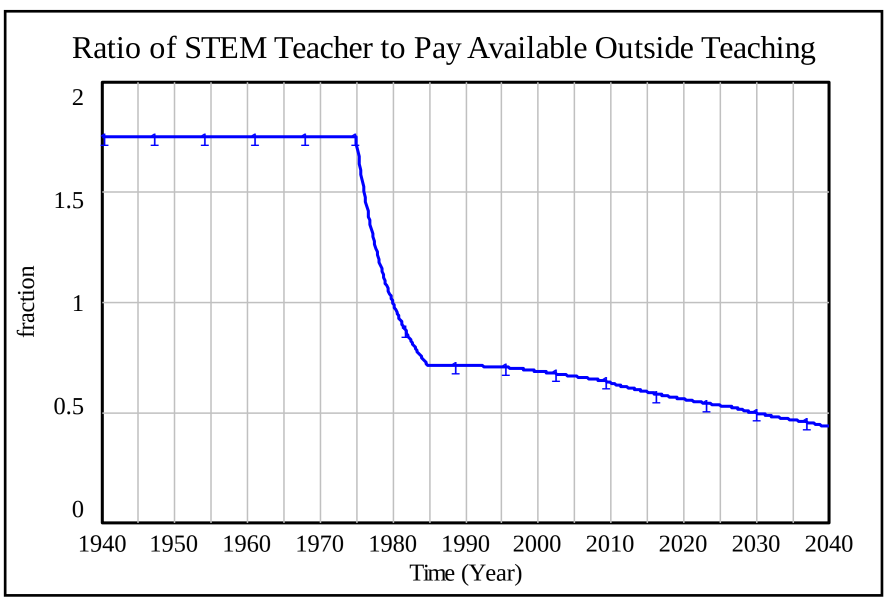
This model is now integrated into the full conceptual model that has been developed over the course of this report. The 'invisible hand' and 'teacher quality' loops intersect at the point where a child either continues in STEM education or falls out of the pipeline. As stated earlier, the model assumes 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 govern.

Model Simulation: History and Momentum Policies

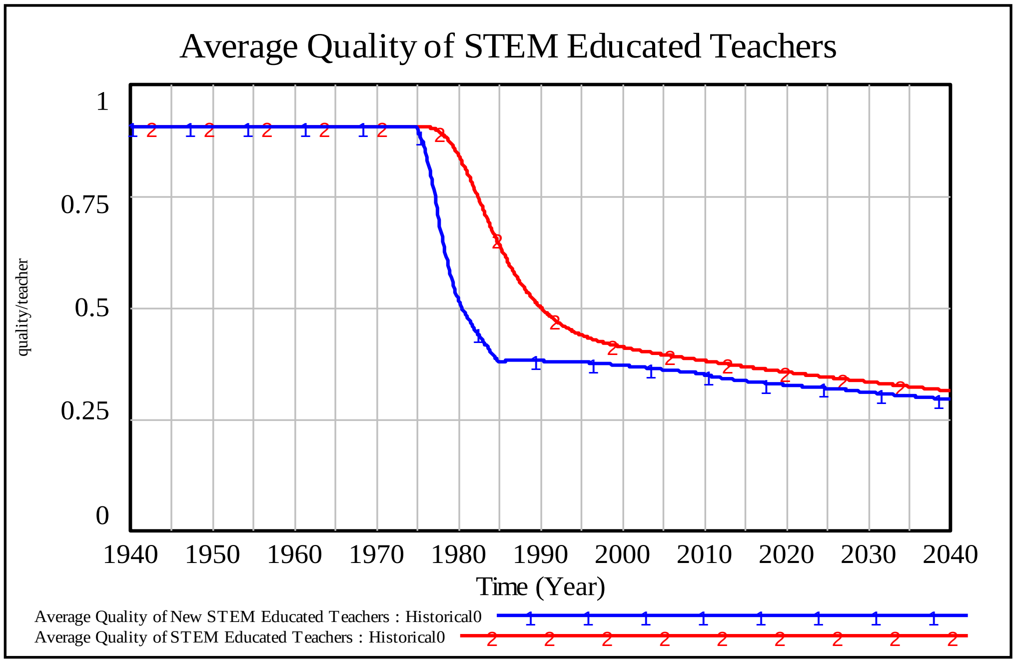
Simulations presented below were run with the following set of characteristics. Some are simplifying assumptions used for the sake of clarity:

- Simulations run from the year 1940 until the year 2040.
- Birth rates are constant.
- Dollars are constant.
- 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.
- Societal demand for STEM products and services are set to increase linearly between 1950 and 2040. This reflects the increasing importance of technology.
- Women enter the workforce starting with a transition period that lasts from 1975 to 1985.

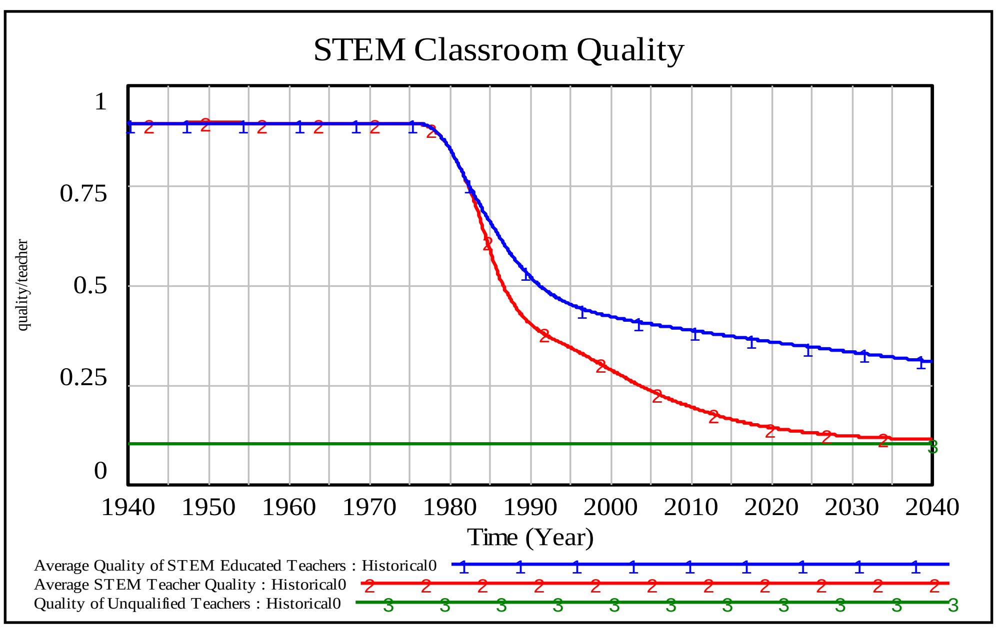
This run is intended to depict a crude representation of what actually happened in the real-world, and what will happen in the future if current policy is maintained. In this set of simulations, liberalization of gender roles occurs and female STEM graduates are allowed to choose freely between teaching 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. 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.



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.

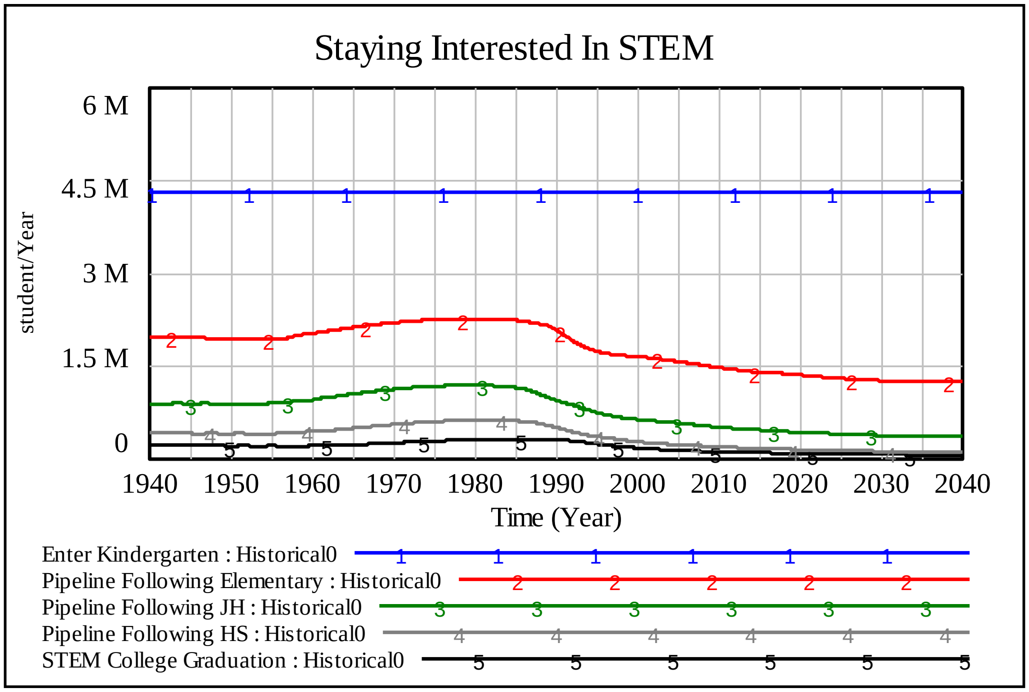


Because teachers are paid a premium prior to 1975 and mobility was restricted, schools are able to draw from the best and brightest of fifty percent of the population. As other more lucrative opportunities open up however, the "Average Quality of New STEM Educated Teachers" drops. Over time, this causes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

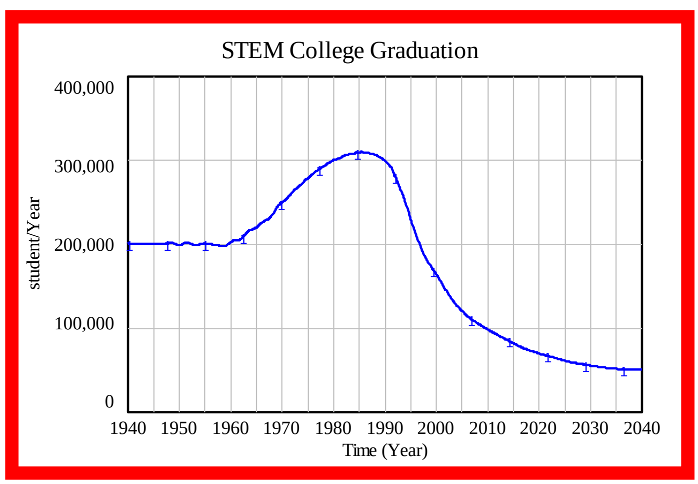


In addition to a quality decline in the average STEM educated teacher, a shortage of those teachers emerges. An increasing percentage of STEM classrooms must be taught by people untrained in STEM subjects. “Average STEM Teacher Quality” is a composite of both “Average Quality of STEM Educated Teachers” and the fraction of classrooms taught by teachers with STEM training. This is the actual quality that students experience.

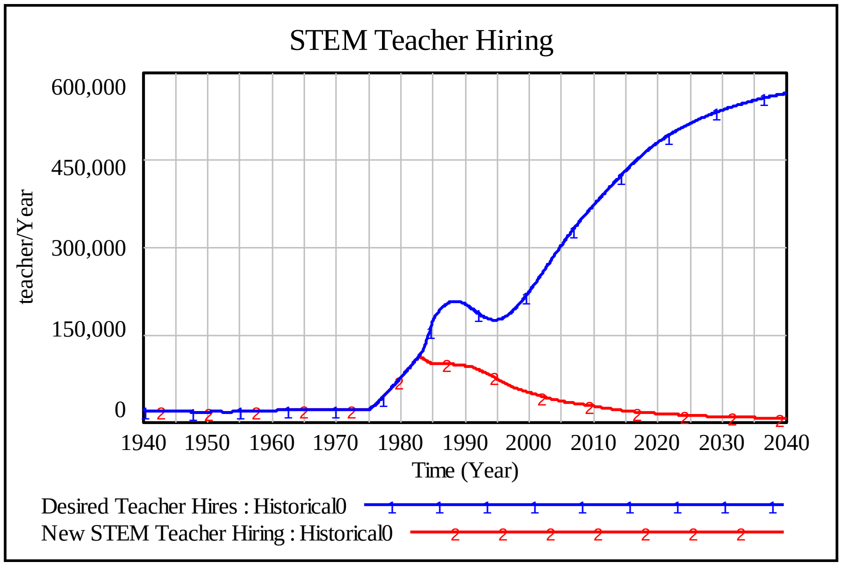
As a result of a decline teacher quality, the number of students in the pipeline at all levels begins to drop after delays. Peaks in the number of students continuing on the pipeline at different grade levels occur at different times because of inertia in the system.



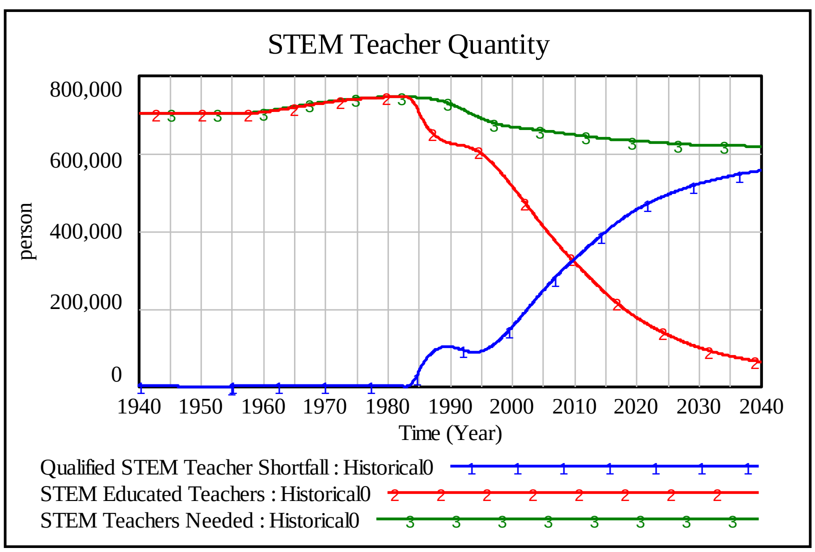
College graduations of STEM students (now shown to full scale) peak in the year 1986 and then drop significantly thereafter in this scenario. This graph qualitatively mimics the actual behavior shown in the real system. One thing to observe is that the number of graduations continues to fall through 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.

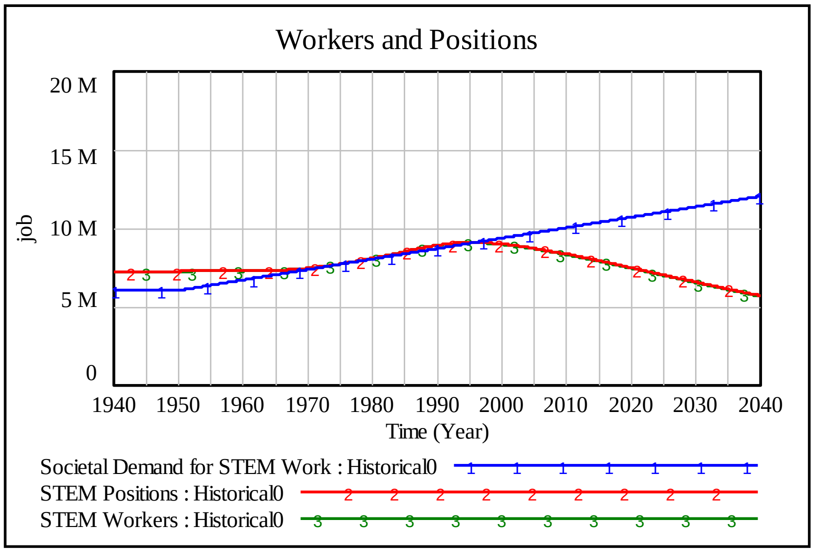


Prior to gender related mobility “New STEM Teacher Hiring” remained flat because hires were able to match retirements. After gender related mobility however, increased turnover opened up many more positions. Many of the STEM graduates during the 1980’s go into teaching to fill the demand left, but STEM 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.

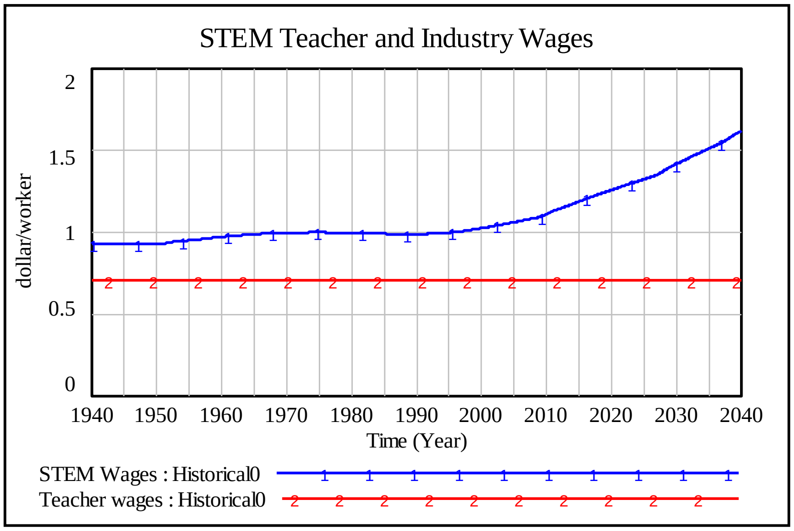


The number of STEM graduates going into teaching cannot keep pace with the "Desired Teacher Hires" so the shortfall of STEM qualified teachers continues to get worse. As a result of the "Qualified STEM Teacher Shortfall", classrooms are taught by teachers without STEM credentials. Sadly, the demand for 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. The problem continues to get worse. Because fewer students make it through the STEM pipeline, fewer become "STEM Workers". As a direct result, the number of STEM workers in the economy begins to drop after 2000 despite increasing demand for the output of STEM work. The number of jobs open in the economy continues to fall as well because STEM workers are only willing to work in increasingly high-pay capacities.





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. The 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 industry responses lead to perverse outcomes over the course of decades.



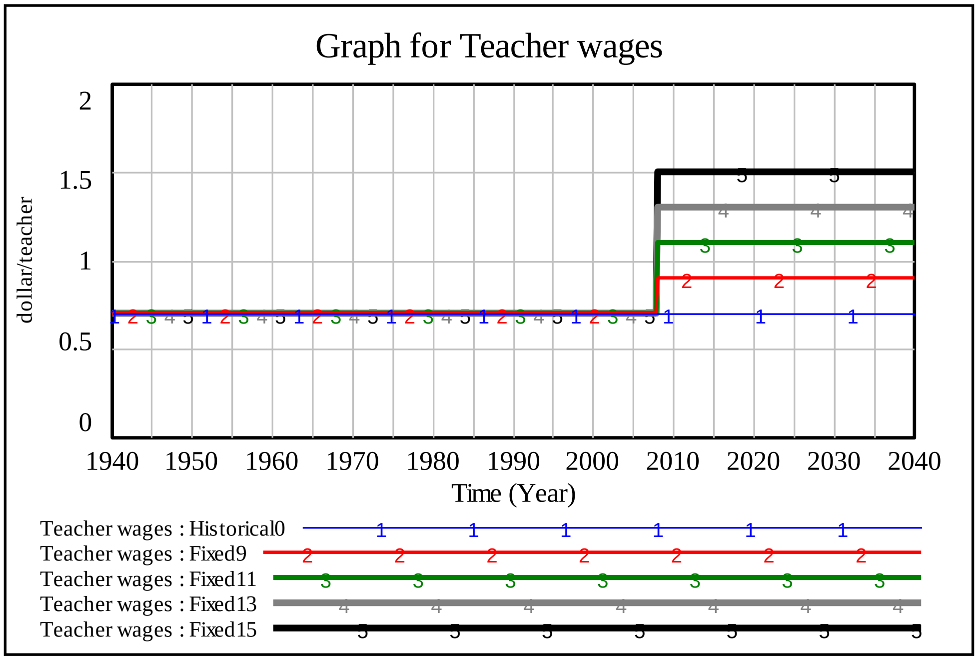
The model presented here is capable of producing behavior in which high pay in STEM fields directly causes future long-term labor shortages in those same fields. The dangerous loop we explored could be influential in any situation in which teachers earn less than practitioners and there is a scarcity 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 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. U.S. STEM industry then begins a downward spiral.

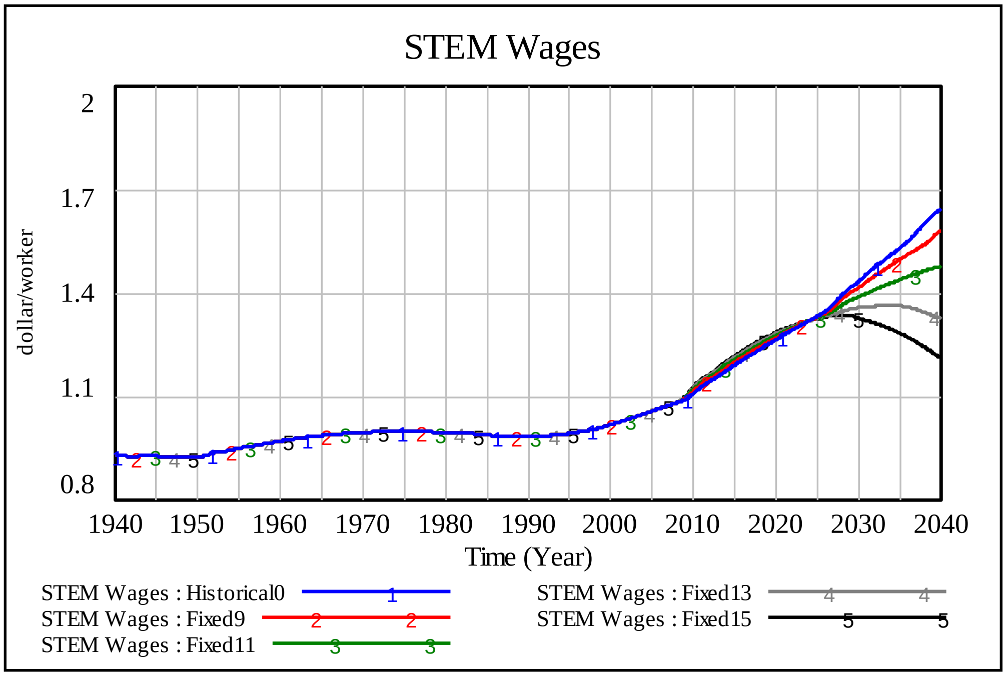
The original problem statement asked why the number of engineers peaked in 1985 and then declined thereafter. This simulation has been able to successfully reproduce a peak in the number of STEM graduates at the same time that wages stay strong or even grow. The simulation predicts that wages will continue growing relative to other jobs in the economy and that the size of the U.S. STEM capable workforce will continue to decline. Increased demand for engineers during the early years of the Cold War 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.

Alternative Future: Testing Multiple Wage Levels

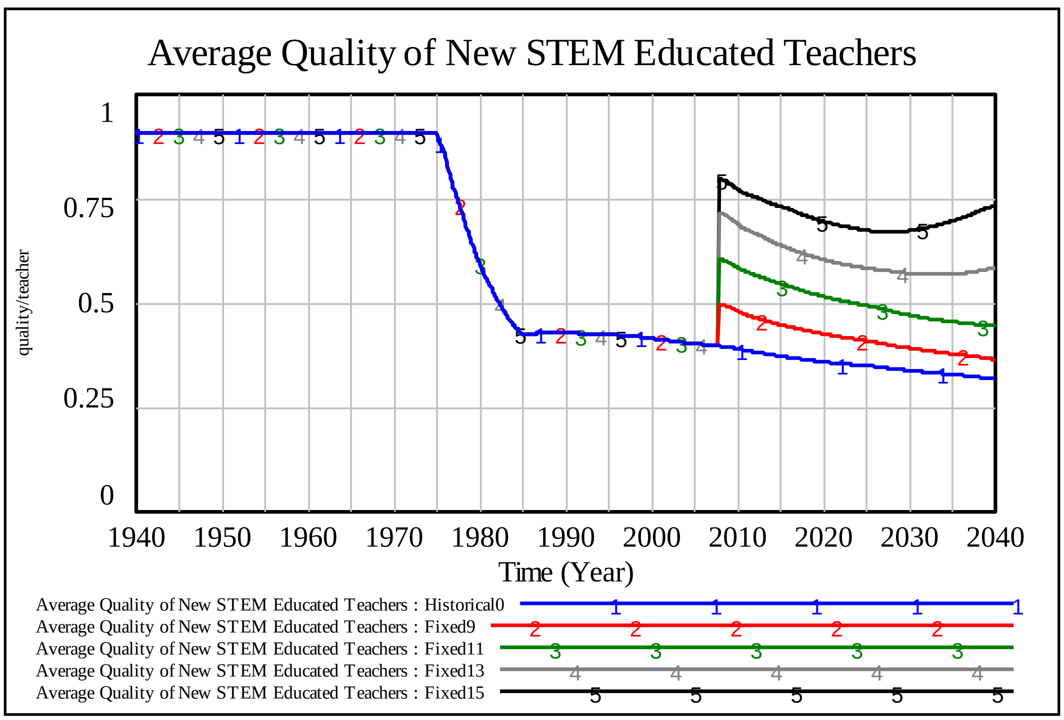


In this set of simulations a variety of fixed wage increases are tested. Wage level in the historical scenario was set at 0.7. Other values tested after 2008 now include 0.9, 1.1, 1.3, and 1.5. In the historical scenario, STEM industry wages had grown to slightly above 1.0 by 2008. Therefore, most wage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

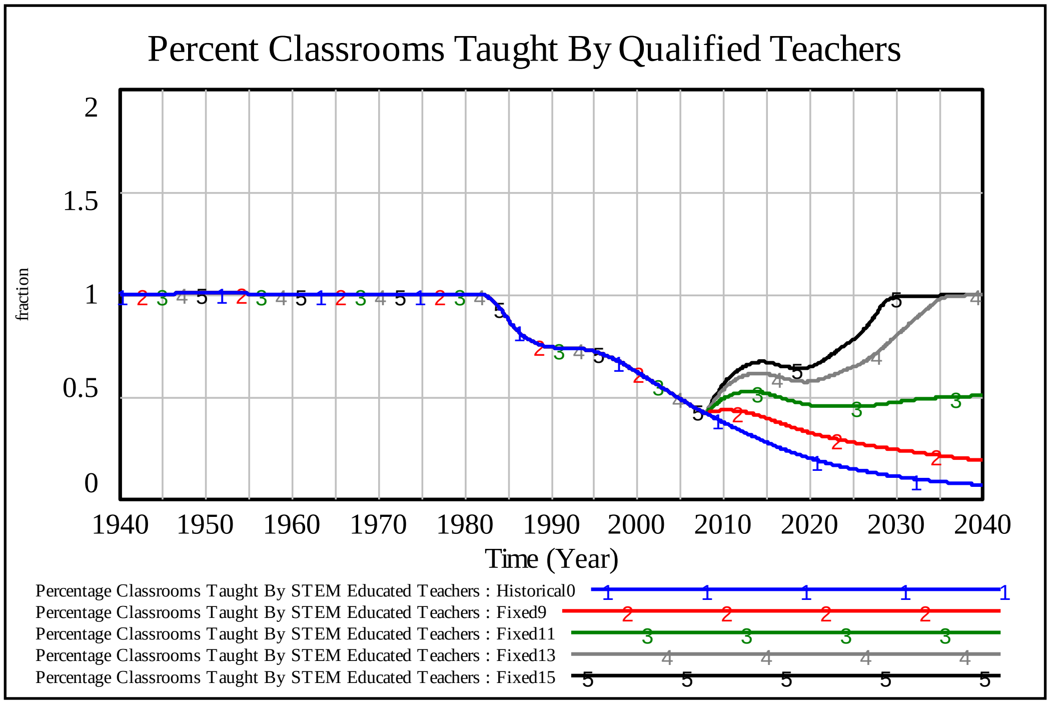
As a result of these tests, "STEM Wages" continue to rise in response to the growing shortage until 2025. In fact, they rise faster than the historical case because more STEM workers are teaching rather than in industry. In 2025, "STEM Wages" exhibit a tipping-point. Low wage increases have virtually 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 wage increases can be made high enough to cause the positive feedback loop to 'tip' into a more virtuous behavior.



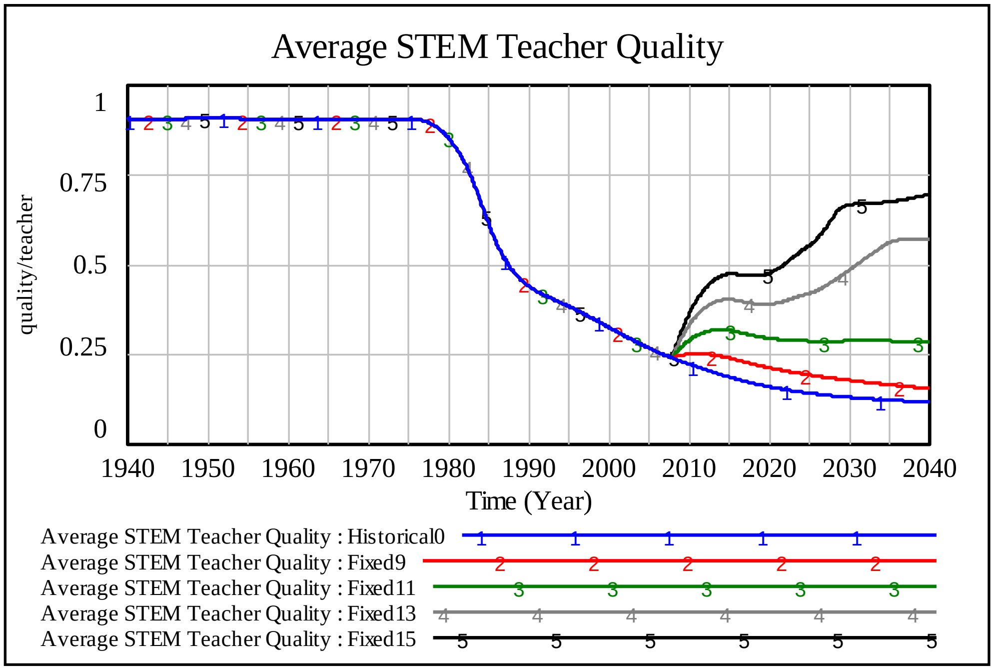
The average quality of new teachers rises significantly in response to the wage increase. As STEM industry wages continue to rise however, the quality again begins to fall. Under some scenarios (when wages in STEM industry drop twenty years later) quality begins to rise again in 2028.



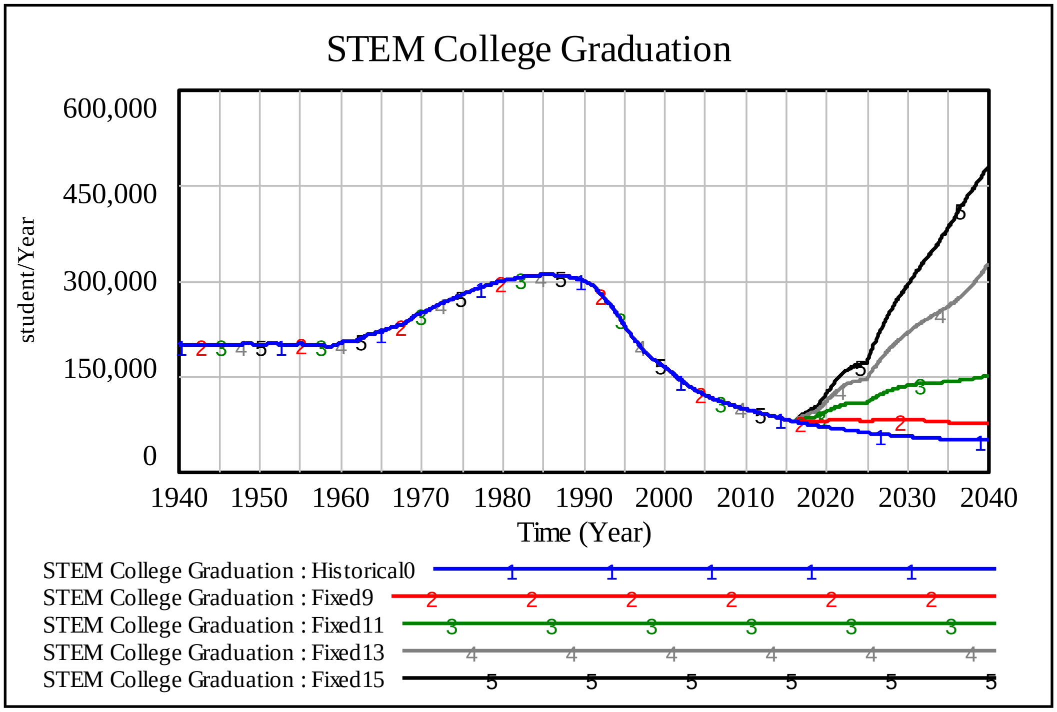
Although a much higher percentage of STEM graduates choose to enter teaching, there is still a shortage of qualified teachers for many years because there is a shortage of STEM graduates available to both industry and to schools that is persistent. This is because even though a majority of graduates 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 generated to fill both school and industry demand. This graph also is indicative of tipping point behavior in the system.



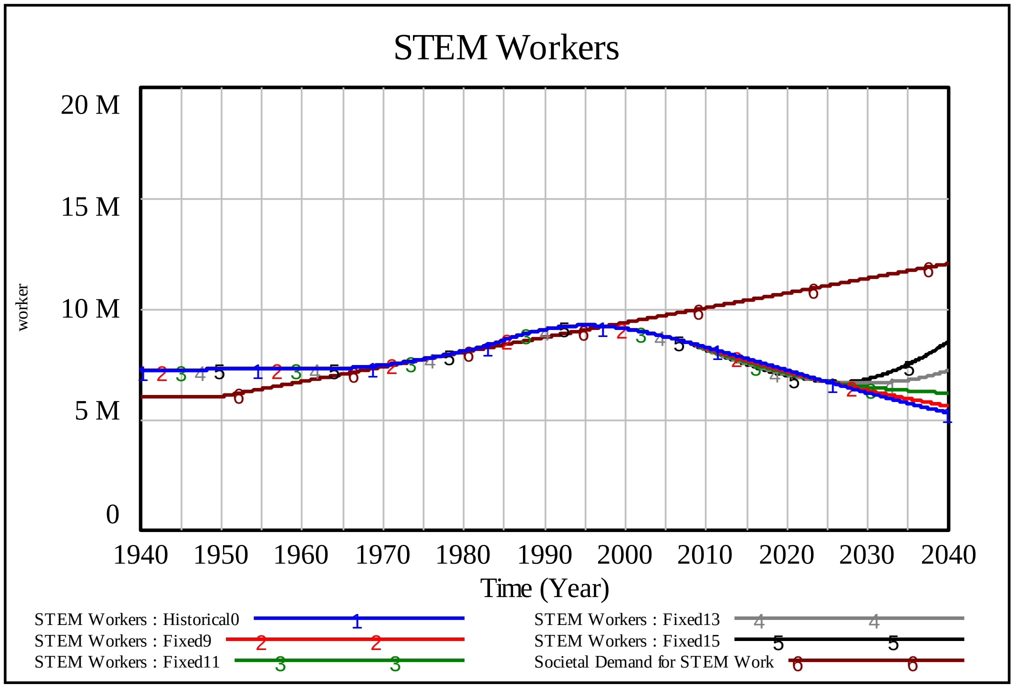
Average STEM teacher quality is a function of both the quality of STEM trained teachers and the percentage of STEM classrooms taught by qualified teachers. Under lower wage increase levels, quality improves marginally but then continues to decline. Under high wage scenarios quality rises substantially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



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



Higher teacher wage increases in 2008 cause STEM industry output to radically change in the year 2028. Note that in this graph STEM workers begin to fill the gap in 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 this gap has significant implications for the U.S. balance of trade.



Insights and Conclusions

The primary goal of this work was to better understand causes 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. 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, a plausible model was created that is capable of reproducing historical system behavior in a qualitative sense. A positive feedback loop was found that can cause normal market mechanisms to turn against themselves. In the current state, the number of STEM graduates is more sensitive to the "teacher quality loop" than the invisible hand of the market.

One conclusion is that high pay for STEM workers and low pay for STEM K-12 teachers could directly cause long-term labor shortages that are self reinforcing. 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) may have triggered unintended behaviors present in the system today. Under their current configuration, our social institutions responsible for developing a technically capable workforce might be stuck in a poor operating region.

Policies intended to correct the situation by increasing teacher wages a small amount had virtually no impact in simulations. Large increases, on the other hand, were able to move the system past a "tipping point" causing it to operate in a fundamentally different way. 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. 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. The tipping point must be crossed so that these gaps begin to close rather than widen further.

Another significant feature displayed prominently in these policy 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 situation. It will take a long time to get out of it. One very important feature to notice about all successful simulated reforms shown 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. 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.

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. Some 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 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. 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.

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. Shortages in the supply of technically-capable people in the labor pool could force U.S. firms to outsource jobs for two reasons. First, if not enough employees exist to meet business demands, then outsourcing must take place. Secondly, shortages in the labor force could 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 engineering wages could remain strong at the same time many of those highly skilled jobs move to other 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 may be 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. If the STEM labor force situation gets bad enough, there are plausible scenarios in which the U.S. high-tech sector 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.

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