STEM Crisis or STEM Surplus?

by

Yi Xue

B.A.Sc. in Engineering Science
University of Toronto, 2012

Submitted to the Engineering Systems Division
in partial fulfillment of the requirements for the degree of

Master of Science in Technology and Policy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2014

© Massachusetts Institute of Technology 2014. All rights reserved.

Signature redacted

Author .................................................................

Engineering Systems Division

\May 12, 2014

Signature redacted

Certified by .............................................................

Richard C. Larson
Mitsui Professor of Engineering Systems
Thesis Supervisor

Signature redacted

Accepted by ..........................................................

Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program
STEM Crisis or STEM Surplus?

by

Yi Xue

Submitted to the Engineering Systems Division
on May 12, 2014, in partial fulfillment of the
requirements for the degree of
Master of Science in Technology and Policy

Abstract

The science, technology, engineering, and mathematics (STEM) workforce is a crucial driver of the U.S. economy. Over the last decade, there has been significant concern regarding the adequacy of the supply of STEM workers to meet the demands of the market. At the same time, many experts have presented evidence that there is a surplus of STEM workers. This thesis tries to reconcile the “STEM Crisis” vs. “STEM Surplus” debate by examining the heterogeneity of the supply and demand for the STEM workforce. The taxicab queueing model is presented as a frameworking metaphor to better understand the variation across different job segments, degree levels, and regions as well as illuminate the probabilistic nature of supply and demand markets. An analysis of the STEM labor market is conducted using an in-depth literature review using available data sources in conjunction with informal sources such as newspaper articles and interviews with company recruiters. Findings indicate that there is significant heterogeneity in the STEM labor market. The academic sector is generally oversupplied. The government sector has shortages in specific areas such as doctorates in nuclear engineering, materials science, and electrical engineering, as well as cybersecurity and intelligence professionals. The private sector also has specific shortages for positions such as petroleum engineers, data scientists, and software developers. At the same time, there are surpluses for graduates in areas like chemistry and physics. The demand and supply also varies according to location and U.S. citizenship. Yes, there is a “STEM Crisis” and no, there is not a “STEM Crisis”. It depends on where you look.

Thesis Supervisor: Richard C. Larson
Title: Mitsui Professor of Engineering Systems
Acknowledgments

I would like to express the deepest gratitude to my thesis supervisor, Professor Richard C. Larson, for his guidance and support. His lessons on the physics of the system and back-of-the-envelope calculations have shaped the way I approach solving complex problems.

I would especially like to thank Professor Navid Ghaffarzadegan of Virginia Tech, for his mentorship and modeling expertise. My sincere thanks go to my colleagues in the Education as a Complex System group for their thoughtful feedback. The eclectic mix of research topics and enriching discussions made our meetings the highlight of my week.

I thank my family, friends, and everyone at TPP for their constant encouragement and support.

I express my gratitude to the National Institutes of Health [Grant 5U01GM094141-02], Massachusetts Institute of Technology and the Natural Sciences and Engineering Research Council of Canada for their support. The discussion and conclusions in this thesis are those of the author and do not necessarily represent the views of the National Institutes of Health, the Natural Sciences and Engineering Research Council of Canada or the Massachusetts Institute of Technology.
3.3.2 Surpluses .............................................. 46
3.3.3 Spatial Differences ................................. 48
3.4 Summary ................................................. 49

4 Policy Discussion ........................................ 51
  4.1 Unintended Consequences of Rapid Funding Increases ............. 52
  4.2 Attracting More Students to STEM ................................ 54
  4.3 Conclusion .............................................. 56

Appendix A Taxicab Queueing Model Derivation ....................... 59

Appendix B $R_0$ Methodology ................................ 63
  B.1 2-Digit CIP Codes ......................................... 64

Appendix C Survey Methodology and Results .......................... 67
  C.1 Consent Form ............................................ 68
  C.2 Interview Questions ...................................... 69
  C.3 Survey Results .......................................... 71
List of Figures


2-1 Queues of taxis (positions) and queues of passengers (workers) can exist simultaneously. ................................................. 24
2-2 State-transition diagram for the STEM job market queueing model. ....... 26
2-3 State probabilities for $N = 10, \lambda/\mu = 6, \bar{L}_{\text{employers}} = 4, \bar{L}_{\text{workers}} = 0.15$. ....... 28
2-4 State probabilities for $N = 10, \lambda/\mu = 9.5, \bar{L}_{\text{employers}} = 0.5, \bar{L}_{\text{workers}} \cong 13$. ....... 28
2-5 State probabilities for $N = 10, \lambda/\mu = 8.5, \bar{L}_{\text{employers}} = 1.4, \bar{L}_{\text{workers}} = 2.8$. ....... 29

3-1 Considerable differences in employment sectors across science and engineering disciplines. Source: National Science Board (2014). .......................... 34
3-2 Number of PhDs age 35-or-younger has increased far more than the number who are in tenure-track positions. Source: Teitelbaum (2007b). ....... 35
3-3 $R_0$ for 794 U.S. institutions by CIP-code, indicating the heterogeneity across 30 different disciplines. Author's calculations. Data sources: CUPA-HR and IPEDS. See Appendix B for full list of CIP codes and descriptions. ....... 36


A-1 State-transition diagram for the STEM job market queueing model.
List of Tables

1.1 Classification of STEM, STEM-Related and Non-STEM Occupations Source: Landivar (2013b) .......................................................... 15
1.2 Characteristics by employment in STEM occupations in 2011. Source: U.S. Census Bureau (2013) .......................................................... 17
2.1 Taxicab queueing model applied to the STEM job market .......................... 24
3.1 $R_0$'s for STEM Disciplines .......................................................... 37
Chapter 1

Introduction

1.1 STEM and the Economy

Over the past century, the U.S. economy has transitioned from one driven by agriculture and labor to a knowledge-based economy, where information and knowledge are the critical resources propelling the economy (OECD, 1996). From Solow (1957)'s seminal work on the economic value of investing in science and technology, it was shown that not only tangibles such as capital and labor promote economic growth, but also intangibles such as research and development, and scientific knowledge. Since then, the strength of the economy in the developed world has been firmly linked to advancements in scientific research, engineering, and technological innovation (National Academy of Sciences, 2007). As we can see in Figure 1-1, the US farm labor productivity increased hundred-fold between 1800 and 2000, much of it being brought about through advancements in science and technology.

Not only has science and technology transformed the economy, it has also affected the way we live. Only in the past century have humans been able to instantaneously converse with people on the other side of the earth with cellular phones or via the internet. From everyday appliances like microwaves and refrigerators to laptop computers and televisions, technology has fundamentally changed how we eat, work, and play. These tangible products of scientific research and development have only come to fruition through fundamental and applied research, infrastructure that supports innovation, and needless to say, a highly skilled science, technology, engineering, and math (STEM) workforce.
Figure 1-1: US farm labor productivity from 1800 to 2000. Source: Moore and Simon (1999).

1.2 What is STEM?

A robust scientific workforce with strong capabilities in STEM is essential for continued innovation and economic competitiveness on the world stage. But what exactly constitutes STEM is not clear cut. The concept was first introduced by the National Science Foundation (NSF) in the 1990’s as an acronym for science, mathematics, engineering and technology (SMET) education (Hampson, 2014). The term, STEM, was coined in 2001 by the director of NSF after reordering the words (Donahoe, 2013). While fields such as computer programming and mechanical engineering are generally considered STEM, there is less consensus on areas such as medicine, architecture, science education, social sciences, and blue-collar manufacturing work.

The Bureau of Labor Statistics’ (BLS) Standard Occupational Classification (2010 SOC) system classifies all workers into 840 occupations. In August 2012, a Standard Occupation Classification Policy Committee (SOCPC) was asked by the White House’s Office of Management and Budget to provide a recommendation for defining STEM based on the
BLS 2010 SOC system to improve comparability of data across agencies. Their definition of STEM encompassed four sub-domains: 1) Life and Physical Science, Engineering, Mathematics, and Information Technology Occupations; 2) Social Science Occupations; 3) Architecture Occupations; and 4) Health Occupations, and five types of occupations: A) Research, Development, Design, or Practitioner; B) Technologist and Technician, C) Post-secondary Teaching; D) Managerial, and E) Sales, which constituted 184 out of the 840 occupations (Standard Occupation Classification Policy Committee, 2012). This definition includes healthcare practitioners, engineering managers, and social scientists, but does not include the skilled trades such as machinists. Based on the SOCPC’s recommendations, the U.S. Census Bureau classified occupations into three groups: STEM, STEM-related, and non-STEM occupations, see Table 1.1 (Landivar, 2013b).

Table 1.1: Classification of STEM, STEM-Related and Non-STEM Occupations

<table>
<thead>
<tr>
<th>High-level occupation aggregation</th>
<th>Occupation group</th>
<th>STEM occupation classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management, business, science, and arts</td>
<td>Management</td>
<td>Non-STEM (exc. computer and information systems managers, architectural and engineering managers, and natural science managers)</td>
</tr>
<tr>
<td></td>
<td>Business and financial operations</td>
<td>Non-STEM (exc. architects; incl. computer and information systems managers, architectural and engineering managers, natural science managers, and sales engineers)</td>
</tr>
<tr>
<td></td>
<td>Computer, math, engineering, and science</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Education, legal, community service, arts, and media</td>
<td>Non-STEM (incl. architects)</td>
</tr>
<tr>
<td></td>
<td>Healthcare practitioners and technicians</td>
<td></td>
</tr>
<tr>
<td>Service</td>
<td>Healthcare support</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Protective service</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Food preparation and serving</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Building and grounds cleaning</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Personal care and service</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Sales and related</td>
<td>Non-STEM (exc. sales engineers)</td>
</tr>
<tr>
<td></td>
<td>Office and administrative support</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Farming, fishing, and forestry</td>
<td>Non-STEM</td>
</tr>
<tr>
<td>Sales and office</td>
<td>Construction and extraction</td>
<td>Non-STEM</td>
</tr>
<tr>
<td>Natural resources, construction, and maintenance</td>
<td>Installation, maintenance, and repair</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Production</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Transportation</td>
<td>Non-STEM</td>
</tr>
<tr>
<td></td>
<td>Material moving</td>
<td>Non-STEM</td>
</tr>
</tbody>
</table>

In 2011, there were 7.2 million STEM workers aged 25 to 64, which constituted 6% of the overall workforce, and an additional 7.8 million workers were employed in STEM-related oc-
cupations (Landivar, 2013b). Table 1.2 shows a detailed breakdown of STEM workers by age, sex, citizenship, and educational attainment. While only 26% of STEM workers were female, 74% of workers in STEM-related occupations (predominantly health-care professions) were female. Thus, while women are underrepresented in STEM occupations (particularly engineering and computer occupations, which comprise more than 80% of STEM occupations), they represent the majority for STEM-related occupations (Landivar, 2013a).

1.3 STEM Workforce Education

Inflow into the STEM labor force occurs primarily through new graduates from educational institutions. Approximately 70% of workers in STEM occupations had a bachelor’s degree or higher, compared to only around 30% of non-STEM occupations (Landivar, 2013b). Thus, most of the inflow is expected to come from new bachelor’s, master’s or doctoral graduates. Looking at the supply of new graduates from the National Science Foundations’ Science and Engineering Indicators Report, there is a clear increasing trend in the number of STEM\(^1\) degrees awarded at all levels over the last 10 years, as seen in Figure 1-2.

Between 2000 and 2010, the number of bachelor’s degrees increased by 32% from around 210,000 to 276,000; master’s degrees increased by 40% from around 59,000 to 83,000; and PhD’s increased 48% from around 20,000 to 29,000 (National Science Board, 2014). In 2010 alone, that is a potential addition of 390,000 people who are educated with bachelor’s degrees or better into a STEM workforce that has around 5 million workers with at least a college education. Using Little’s Law of queues, a simple back-of-the-envelope calculation tells us that the average length of a career in a STEM occupation would need to be around 12.8 years in order to absorb all 390,000 new STEM workers annually \(^2\). Given that many graduates initially find work outside of STEM occupations, we expect the actual length of a career in STEM to be even longer.

\(^1\)STEM degrees is defined to be degrees in engineering, natural sciences, and mathematics, as categorized in the NSF Indicators 2014 Report

\(^2\)Little’s Law: \(L = \lambda \cdot W\), 5,000,000 = 390,000 \cdot W, which implies \(W = 12.8\) years
Table 1.2: Characteristics by employment in STEM occupations in 2011. Source: U.S. Census Bureau (2013)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Total</th>
<th>STEM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Percent</td>
</tr>
<tr>
<td>Total</td>
<td>132,910,420</td>
<td>100</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 to 24 years</td>
<td>16,465,112</td>
<td>12.4</td>
</tr>
<tr>
<td>25 to 34 years</td>
<td>30,158,891</td>
<td>22.7</td>
</tr>
<tr>
<td>35 to 44 years</td>
<td>30,744,454</td>
<td>23.1</td>
</tr>
<tr>
<td>45 to 54 years</td>
<td>32,998,018</td>
<td>24.8</td>
</tr>
<tr>
<td>55 to 64 years</td>
<td>22,543,945</td>
<td>17</td>
</tr>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>69,410,681</td>
<td>52.2</td>
</tr>
<tr>
<td>Female</td>
<td>63,499,739</td>
<td>47.8</td>
</tr>
<tr>
<td><strong>Race and Hispanic Origin</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White alone</td>
<td>101,427,282</td>
<td>76.3</td>
</tr>
<tr>
<td>Black or African American alone</td>
<td>14,553,259</td>
<td>10.9</td>
</tr>
<tr>
<td>Asian alone</td>
<td>7,047,629</td>
<td>5.3</td>
</tr>
<tr>
<td>American Indian and Alaska Native alone</td>
<td>879,792</td>
<td>0.7</td>
</tr>
<tr>
<td>Native Hawaiian and Other Pacific Islander alone</td>
<td>208,804</td>
<td>0.2</td>
</tr>
<tr>
<td>Some Other Race alone</td>
<td>6,205,834</td>
<td>4.7</td>
</tr>
<tr>
<td>Two or More Races</td>
<td>2,587,820</td>
<td>1.9</td>
</tr>
<tr>
<td>Hispanic or Latino (of any race)</td>
<td>20,747,680</td>
<td>15.6</td>
</tr>
<tr>
<td><strong>Citizenship</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Native-born</td>
<td>110,476,466</td>
<td>83.1</td>
</tr>
<tr>
<td>Foreign-born, citizen</td>
<td>10,187,565</td>
<td>7.7</td>
</tr>
<tr>
<td>Foreign-born, not a citizen</td>
<td>12,246,389</td>
<td>9.2</td>
</tr>
<tr>
<td>Less than high school diploma</td>
<td>12,108,097</td>
<td>9.1</td>
</tr>
<tr>
<td>High school graduate</td>
<td>33,889,052</td>
<td>25.5</td>
</tr>
<tr>
<td>Some college</td>
<td>32,390,520</td>
<td>24.4</td>
</tr>
<tr>
<td>Associate's degree</td>
<td>11,825,331</td>
<td>8.9</td>
</tr>
<tr>
<td>Bachelor's degree</td>
<td>27,481,228</td>
<td>20.7</td>
</tr>
<tr>
<td>Master's degree</td>
<td>10,667,928</td>
<td>8</td>
</tr>
<tr>
<td>Professional degree</td>
<td>2,814,576</td>
<td>2.1</td>
</tr>
<tr>
<td>Doctorate degree</td>
<td>1,733,688</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Industry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agriculture, forestry, fishing and hunting, and mining</td>
<td>2,512,497</td>
<td>1.9</td>
</tr>
<tr>
<td>Construction</td>
<td>8,302,493</td>
<td>6.2</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>14,193,598</td>
<td>10.7</td>
</tr>
<tr>
<td>Wholesale trade</td>
<td>3,698,052</td>
<td>2.8</td>
</tr>
<tr>
<td>Retail trade</td>
<td>15,216,200</td>
<td>11.4</td>
</tr>
<tr>
<td>Transportation and warehousing, and utilities</td>
<td>6,692,600</td>
<td>5</td>
</tr>
<tr>
<td>Information</td>
<td>2,831,141</td>
<td>2.1</td>
</tr>
<tr>
<td>Finance and insurance, and real estate</td>
<td>8,731,387</td>
<td>6.6</td>
</tr>
<tr>
<td>Professional, scientific, and management services</td>
<td>14,268,752</td>
<td>10.7</td>
</tr>
<tr>
<td>Educational services, health care and social assistance</td>
<td>30,983,153</td>
<td>23.3</td>
</tr>
<tr>
<td>and social assistance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arts, entertainment, recreation, accommodation</td>
<td>12,202,032</td>
<td>9.2</td>
</tr>
<tr>
<td>and food services</td>
<td>6,464,549</td>
<td>4.9</td>
</tr>
<tr>
<td>Other services</td>
<td>6,813,966</td>
<td>5.1</td>
</tr>
</tbody>
</table>
1.4 STEM Shortage or Surplus?

Despite the overall growth in science and engineering degrees over the years, there is still a growing concern over the potential shortage of a STEM workforce necessary to sustain the U.S.'s innovation enterprise, global competitiveness and national security. The most notable publication being the National Academies' Report entitled *Rising Above the Gathering Storm*, which called for improvements to K-12 science and mathematics education, and increasing the attractiveness of higher education, amongst other suggestions. The report stressed the need for maintaining the U.S.'s competitive edge in order to attract, develop, and retain the top STEM talent. It highlighted troubling factors in a number of areas: low retention rates in STEM, relative decline of U.S. citizens in science and engineering graduate school enrolment, and lower percentages of STEM graduates compared to other developed countries (National Academy of Sciences, 2007).

In a 2012 report by the U.S. Congress Joint Economic Committee (2012), it states that the current STEM workforce is falling short of demands in both STEM and non-STEM
occupations. The report points to the fact that despite the overall growth the STEM degrees, the relative share of STEM degrees compared to non-STEM has declined at the associate’s, bachelor’s and master’s levels.

International students account for a significant number of natural science and engineering degree graduates, especially at the doctoral level, and many of them leave the country after they finish their education. In 2011, foreign students accounted for almost 4% of STEM degrees awarded at the bachelor’s level; 26% of STEM degrees awarded at the master’s level, and 34% at the doctorate level (National Science Board, 2014). In certain fields, such as electrical engineering, foreign doctoral students account for a staggering 65% of all degrees awarded. The overall increase in doctoral recipients has only seen a growing share of engineering and science degrees awarded to foreign students, as seen in Figure 1-3. Thirty-eight percent of non-U.S. citizens who obtained a science or engineering doctorate in 2004 left the U.S. within 5 years. There is growing concern that U.S. is starting to fall behind in attracting and retaining talent now that other nations are following the U.S. education system’s model.

![Chart showing the share of STEM doctoral degrees granted to U.S. domestic students and STEM doctorates as a share of all doctorates awarded.](image)

Figure 1-3: Share of STEM doctoral degrees going to U.S. domestic students between 1985 and 2006, and STEM doctorates as a share of all doctorates awarded, between 1985 and 2006. Source: U.S. Congress Joint Economic Committee (2012).

Although the U.S. produces the most STEM degree holders amongst OECD countries
in absolute terms, the share of students receiving STEM bachelor’s degrees (15% in U.S.) is lower than many of U.S.’s competitors such as Canada (22%), Japan (24%), Germany (29%), and was ranked at just 27th out of 30 OECD countries (U.S. Congress Joint Economic Committee, 2012).

Economic projections have forecasted a tremendous gap in the supply of STEM professionals. The Business Roundtable called for a doubling of STEM degrees between 2005 and 2015 to remain competitive on the world stage (Business Roundtable, 2005). According to a President’s Council of Advisors on Science and Technology (PCAST) Report (2012), there will be a need for 1 million more STEM professionals than what the U.S. is currently expected to produce over the next decade. The U.S. would need to increase yearly production of undergraduate STEM degrees by 34% annually over current rates to match the forecasted demand. However, between 2000 and 2010, the expansion of the STEM workforce was much slower than the rate at which STEM graduates were being produced: around 560,000 over 10 years compared to over 280,000 per year. This begs the question: is there a shortage?

There are many who would disagree. Testifying before the U.S. House of Representatives, Teitelbaum (2007a), opined that there are no general shortages of scientists and engineers. In fact, he went even further to say that there was even evidence suggesting surpluses: that there are significantly more science and engineering graduates in the U.S. than attractive positions available in the workforce. Similarly, Lowell and Salzman (2007) have found more science and engineering graduates than jobs, citing that there are 15.7 million workers who report at least one degree in a science or engineering field, but only 4.8 million workers are in a science and engineering occupation. Looking at the STEM labor market, Salzman et al. (2013) concluded that for every two students graduating with a U.S. STEM degree, only one is employed in STEM; and of the computer science graduates who were not employed in IT, 32% attributed it to lack of available jobs and 53% said they found better opportunities outside of IT occupations.

During the 1990s and early 2000s before the dot-com bust, there was a steep increase in employment and wages for computer and IT occupations (Salzman et al., 2013). On the contrary, Butz et al. (2003) observed that unemployment rates for certain groups such as chemists, mathematicians and recent biomedical PhDs saw a general increase in the 1990s,
despite the strong overall economy, which suggests a surplus, not a shortage. Their analysis found that there was a "shortage" only in the sense that American production of STEM graduates appears low in comparison to foreign gains, not in terms of decreasing STEM graduates nor employer need.

1.5 Government Policies

Government initiatives have been undertaken from both the Bush Administration and the Obama Administration to improve STEM higher education and increase STEM graduates. In 2006, President George W. Bush established the American Competitiveness Initiative to increase federal funding for research and development, and U.S. higher education graduates in STEM fields (Domestic Policy Council, 2006). President Obama launched the Educate to Innovate Campaign for Excellence in Science, Technology, Engineering and Mathematics Education in November 2009 to foster public-private partnerships and encourage students to pursue careers in STEM (The White House, 2014).

These kinds of government initiatives are not only limited to the U.S., but are pervasive across the developed world. Australia, United Kingdom, and Canada all have similar concerns regarding their STEM workforces (Office of the Chief Scientist, 2013, Harrison, 2012, Komarnicki, 2012).

1.6 Problem Definition

There appears to be a conundrum. Is there a STEM crisis or a surplus? At one end of the spectrum, we have reports deploring the state of the STEM worker shortage: two vacant jobs for each STEM job-seeker and STEM wages are higher than all other occupations with the same level of education. At the other end of the spectrum, we have studies that have depicted the exact opposite situation: STEM wages have remained flat, with real wages hovering at late 1990s levels; and only one out of two STEM graduates being hired into a STEM job. Perhaps the answer is both. STEM covers a diverse array of occupations from mathematicians to biomedical researchers, and at degree levels from bachelor’s to master’s to PhD’s. Some occupations may have a shortage of qualified talent, such as nuclear and
electrical engineering PhDs who are U.S. citizens; and in other areas there exists a surplus, such as biology PhDs aiming to become professors. The goal of this study is to examine the heterogeneous nature of STEM occupations, to develop a better understanding of the oversupply or undersupply of STEM graduates, and to inform STEM higher education policy. The analysis will focus on characterizing the different occupations within STEM based on current literature, journal articles, as well as anecdotal evidence through surveys conducted by the author.

The strength of the U.S. STEM workforce is a pressing concern for U.S. policy as it influences the U.S.'s ability to innovate and remain competitive globally. A deeper understanding of the heterogeneity behind blanket statements of surpluses and shortages will help decision makers create better policies that tailor to the STEM workforce's needs.

The thesis is organized as follows: Chapter 2 presents the taxicab queueing model, which is used as a frameworing metaphor to describe the variation in supply and demand needs across different STEM job segments; an in-depth analysis of the STEM labor market is presented in Chapter 3; and Chapter 4 concludes the thesis by examining current policies on STEM.
Chapter 2

Modeling and Methodology

The supply and demand of STEM workers is a complicated labor market system that varies depending on degree-level, occupation, and location. This thesis presents an analysis of the heterogeneity of the STEM labor market, using the taxicab queueing model as a frameworking metaphor.

2.1 Taxicab Queueing Problem

The taxicab queue is a classic queueing theory problem, first documented in literature by Kendall (1951). The problem can be formulated as follows: passengers arrive at a taxi stand independently in a Poisson manner, where $\lambda$ is the mean number of arrivals per unit of time. There are $N$ taxis in the fleet. When they are available and waiting for passengers (who arrive in a Poisson manner at a rate $\lambda$), the taxis form a queue of available taxis. Taxis that are busy transporting passengers arrive back at the taxi stand according to a conditional Poisson process, which depends on the number of taxis that are currently busy. We assume that each taxi trip has an average duration of $1/\mu$ and that the probability density function of the duration of each trip is drawn from a negative exponential density with a mean of $1/\mu$. If we have $k$ taxis that are busy, then we have an arrival rate back to the taxi stand of $k\mu$. At the queueing point, each taxi is matched up to a passenger. This means that we cannot have both taxis and passengers queueing at the same time. If there are passengers waiting in queue, then we have a positive queue; and if there are taxis waiting in queue, then we have what we call a negative queue. A queue length of zero means that there are neither
taxis nor passengers waiting.

The behavior of each queue is dependent upon the average duration of taxi service \(1/\mu\), size of the taxi fleet \(N\), and the average passenger arrival rate \(\lambda\). These parameters are different for each taxicab queue in a city. At a given time, some locations may have a queue of taxis waiting for passengers, while other locations may have a queue of passengers waiting for taxis. Looking at the STEM job market we have a similar scenario: we have different queues for each STEM job category (see Figure 2-1 and Table 2.1).

![Taxi and Stem Jobs](http://cen.acs.org/content/dam/cen/90/45/09045-ofc.jpg, http://www.weshatetowaste.com/wp-content/uploads/2012/04/TaxiCabLine.png, taxi icon is a free vector image)

Figure 2-1: Queues of taxis (positions) and queues of passengers (workers) can exist simultaneously.

Table 2.1: Taxicab queueing model applied to the STEM job market

<table>
<thead>
<tr>
<th>Taxi Stand</th>
<th>Segment of STEM Job Market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passengers</td>
<td>STEM Workers</td>
</tr>
<tr>
<td>Taxis</td>
<td>Employers or Positions</td>
</tr>
<tr>
<td>Finite Taxi Fleet</td>
<td>(N)</td>
</tr>
<tr>
<td>Passenger Arrival Rate</td>
<td>(\lambda)</td>
</tr>
<tr>
<td>Taxi Service Rate</td>
<td>(\mu)</td>
</tr>
<tr>
<td>Queue of Taxis</td>
<td></td>
</tr>
<tr>
<td>Queue of Passengers</td>
<td></td>
</tr>
</tbody>
</table>

Using the taxicab metaphor, each taxi-passenger system represents a narrow segment of the STEM job market.
of the STEM employment system. Employers or positions can be thought of as a finite number of taxicabs and STEM workers can be thought of as a stream of passengers. We have employers who are searching for employees, which is analogous to taxis waiting for passengers. In the other queue, we have STEM workers who are searching for jobs, similar to how passengers are waiting for taxis. If the number of employers searching for employees outnumber the number of STEM workers, we have a queue of taxis, which manifests in the real world as a STEM shortage. If the number of STEM workers outnumber the number of employers, we have a queue of STEM workers, which means that there is a STEM surplus. If the number of employers equals the number of STEM workers, then we have a momentary match between supply and demand and there is no queue.

In a portfolio of STEM job categories mirroring the U.S. STEM job market, we expect to see queues of employers for some occupations, and queues of workers for other occupations. Furthermore, due to probability alone, the length of the queue can fluctuate over time. A job category that has an excess of workers will on occasion have a deficit of workers, and vice versa. Thus, we expect a heterogeneous mixture of queues for STEM job categories, rather than a STEM Crisis across the board.

2.2 Problem Formulation

Mathematically, the problem can be formulated identically to the taxi-cab scenario. A state-transition diagram for the model is shown below (see Figure A-1. The queueing system is described by the state variable, $i$. If $i$ is positive, it represents the number of workers in the queue, and if $i$ is negative, it represents the number of employers or positions waiting to be filled in the queue. The probability of being in state $i$ at time $t$ is given by $\pi_{(i)}(t)$. Each state is represented by a circle and states are connected to each other by directed links. Each directed link has an associated state transition rate. The state transition rate from state $i$ to state $i + 1$ (shown as the top set of directed links) is $\lambda$, the mean arrival rate of STEM workers. The state transition rate from state $i$ to state $i - 1$ (shown as the bottom set of directed links) is dependent on the number of positions that are currently occupied. If the average position turnover rate is $\mu$, and there are $k$ occupied positions in state $i$, then the
associated transition rate to state $i - 1$ is $\mu$ for the directed link.

Using this model, we can examine the system in steady state. When the system reaches equilibrium after some time, this implies that the state probabilities, $\pi(i)(t)$, become independent of time $(t)$, and reach a set of constant values. Thus, we can write a system of linear equations, which are the equilibrium equations of the queueing system. This can be done by inspection using the state-transition diagram. We solve this system of equations by expressing all of the steady-state probabilities in terms of a single state’s probability, in this case we used $\pi(0)$, and using the fact that all the state probabilities must sum to one. In order for the system to reach a steady state solution, $\lambda$ must be less than $N\mu$, otherwise, the queue for STEM workers will grow indefinitely and there is no equilibrium. Assuming $\lambda < N\mu$, the probability of being in state $(k)$, $\pi(k)$, was found to be as follows (see Appendix A for derivation):

$$\pi(k) = \begin{cases} 
\frac{N!}{(N-i)!} \left(\frac{\mu}{\lambda}\right)^i \pi(0) & \text{if } -N \leq k \leq 0 \text{ queue of positions} \\
\frac{1}{N!} \left(\frac{\mu}{\lambda}\right)^i \pi(0) & \text{if } k > 0 \text{ queue of workers}
\end{cases}$$

(2.1)

Where $\pi(0) = \frac{1}{e^{\frac{\lambda}{\mu}} (\frac{\mu}{\lambda})^{N+1} \Gamma(N+1, \frac{\lambda}{\mu}) \frac{1}{1 - \frac{\lambda}{N\mu}}}$ and $\Gamma(a, x)$ is the upper incomplete gamma function.

Using the steady-state probabilities, we can also find other interesting quantities such as the expected number of employers ($\bar{L}_{\text{employers}}$) and the expected number of STEM workers ($\bar{L}_{\text{workers}}$) waiting in queue using these steady state probabilities. This is also the expected length of the queue, which is a summation of the length of queue in state $i$, multiplied by the probability of being in state $i$.

$$\bar{L}_{\text{employers}} = \sum_{i} i \pi(i) = \sum_{i=0}^{N} \frac{i \cdot N!}{(N-i)!} \left(\frac{\mu}{\lambda}\right)^i \pi(0)$$

(2.2)

Figure 2-2: State-transition diagram for the STEM job market queueing model.
\[ L_{\text{workers}} = \sum_{i} i \pi(i) = \sum_{i=0}^{N} \frac{i}{N^i} \left( \frac{\lambda}{\mu} \right)^i \pi(0) \]  

\[ (2.3) \]

2.3 Examples of Varying Steady-State Probabilities

In this section, we will explore the interactions between the variables: the average arrival rate of STEM workers (\(\lambda\)), the average position turnover rate (\(\mu\)), and the number of employers or positions (\(N\)). This section contains three scenarios: a STEM shortage, a STEM surplus, and a balanced market. The following examples are intended to showcase different possible scenarios, so the numerical values of the parameters are merely illustrative. The number of positions was fixed at \(N = 10\), while the ratio of STEM worker arrival to position turnover rate (\(\lambda/\mu\)) varied across the three examples. As we can see from the equation for steady-state probability, it is the ratio of \(\lambda\) to \(\mu\) that changes the behavior of the queue, rather than their absolute magnitudes.

2.3.1 Case 1: STEM Shortage

In this scenario (\(N = 10, \lambda/\mu = 6\)), we have a STEM shortage in steady-state, meaning that for most of the time, there will be a queue of employers rather than a queue of STEM workers. More precisely, 90\% of the time, there will be a queue of employers and for only 6\% of the time, there will be a queue for workers. In the remaining 4\% of the time, there is no queue. The average queue length for the employers (\(L_{\text{employers}}\)) is 4, meaning that we expect almost half of them to be in queue searching for employees. Whereas the average queue length for the STEM workers (\(L_{\text{workers}}\)) is only 0.15, so we expect there to be practically no queue at all. If we increase \(N\), this will further magnify the shortage, as even more employers are searching for employees. Figure 2-3 below shows the distribution of the state probabilities.
2.3.2 Case 2: STEM Surplus

In this case \((N = 10, \lambda/\mu = 9.5)\), we have a STEM surplus when the system reaches equilibrium. There will be a queue of employers 17\% of the time, no queue at all 4\% of the time, and for 79\% of the time, there will be a queue for workers. The average queue length for the employers \(\bar{L}_{\text{employers}}\) is 0.5, while the average queue length for the STEM workers \(\bar{L}_{\text{workers}}\) is almost 13. As \(\lambda\) approaches \(N\mu\), the expected length of the queue for STEM workers gets exponentially longer. Figure 2-4 below shows the distribution of the state probabilities. In this scenario, the distribution of probabilities is much flatter, with the highest probability state being around 4\% (compared to over 15\% in Case 1) and also a much longer right tail probability.

![Figure 2-4: State probabilities for \(N = 10, \lambda/\mu = 9.5, \bar{L}_{\text{employers}} = 0.5, \bar{L}_{\text{workers}} \cong 13\).]
2.3.3 Case 3: Balanced Market

Finally, we have the case for a balanced market \((N = 10, \lambda/\mu = 8.5)\), where there is a queue for employers approximately half the time and a queue for workers the other half. It is interesting to note that in a balanced market, we will still generally have queues, but they are much shorter on average. For example, in this scenario, the average queue length for employers \((\bar{L}_{\text{employers}})\) is 1.4, while the average queue length for STEM workers \((\bar{L}_{\text{workers}})\) is 2.8. A balanced market under steady-state conditions simply means that there is an equal likelihood of there being a shortage of workers or a shortage of positions, not that there will not be queues. Even in steady-state, there will be random fluctuations in queue length (see Figure 2-5 for distribution of probabilities).

![Figure 2-5: State probabilities for \(N = 10, \lambda/\mu = 8.5, \bar{L}_{\text{employers}} = 1.4, \bar{L}_{\text{workers}} = 2.8\).]

2.4 Research Method

This queueing theory framework provides a novel approach to looking at the STEM labor market and the “STEM Crisis” vs. “STEM Surplus” conundrum. Much in the same way that the demand and supply of taxicabs and passengers varies by type, so does the demand and supply of STEM workers. Just as there are separate lines for taxi-cabs that accept credit cards versus ones that do not, there are distinct lines for each type of STEM occupation. The demand for doctorates in mechanical engineering is different from the demand for bachelors in mechanical engineering, and the supply of doctorates in biomedical sciences is different from the supply of doctorates in physics. Furthermore, there are spatial differences as well.
At an airport, a queue of waiting taxis may be common sight, but outside of a hotel, there may be a queue of waiting passengers. Analogously, the demand for petroleum engineers in Texas is different from the demand for petroleum engineers in Massachusetts. There may not be a “STEM Crisis” in all job categories, but instead in particular ones, at certain degree-levels and locations. Additionally, this model captures the probabilistic nature of supply and demand markets. The arrival rates of both employers and STEM workers to the job market are uncertain. On occasion, a job segment that traditionally has a shortage of workers will have a surplus and similarly, a job segment that traditionally has a surplus of workers will sometimes have a shortage. Thus, this thesis will analyze the heterogeneous nature of the supply and demand for STEM workers, using the taxicab queueing model as a metaphor.

The STEM labor market is a complex system involving many actors: students, current STEM workers, educational institutions, government and the private sector. Depending on the STEM segment, we have each of the levers influencing the market to varying degrees over time. For example, the National Institutes of Health (NIH) doubled its budget between 1998 and 2003, which had a profound impact on the demand for biomedical scientists and doctorates. Meanwhile, this coincided with the dotcom bust, which hurt the employment of the IT sector. The behavior of each job segment varies over time and location. Detailed data on STEM labor markets tends to be sparse. On the supply side, there are problems with underreporting of surpluses. The unemployment rate of STEM graduates is consistently low, but does not reflect those who are underemployed or have switched fields. On the demand side, there is little available data on job openings in aggregate for various STEM job segments. Hence, the analysis of the STEM labor market is conducted using an in-depth literature review using available data sources in conjunction with informal sources such as newspaper articles and interviews of company recruiters. Due to the small sample size \( n = 18 \), the interviews may be limited in generalizability, but supplement the overall literature on the subject. The objective of the study is to highlight the heterogeneity of the demand and supply for STEM workers, rather than to paint a complete picture of the supply and demand across all STEM job segments.

Interviews involved a survey and an open-ended interview (see Appendix C for details). The survey contained short-answer questions that guided the open-ended interviews, such
as the company's industry, size, and positions. The major difficulty in the data collection process has been the response rate, which was around 20%. Thus, there is a possibility that there was a self-selection effect for respondents. Hence, interview results are only included when they supplement existing literature on the field, or fill in missing gaps.
Chapter 3

Literature Survey and Results

The literature on the supply and demand of STEM workers tends to lean heavily in one direction or the other: with one side proclaiming an impending STEM crisis and the other side asserting a STEM surplus. This shortage versus surplus conundrum can be resolved by examining the STEM market on a deeper level. By segmenting the STEM labor market based on different disciplines, sectors and skill levels, we find that there is considerable heterogeneity in the supply and demand of workers. We have both queues of taxis and queues of passengers, not just the presence of one or the other.

The analysis of the STEM labor market will be broken down into three main employment sectors: academia, government, and private sector, and then further narrowed down by specific job categories and disciplines. Figure 3-1 below shows employment sectors of the college-educated U.S. science and engineering workforce by their broad occupational category. For engineers and computer and mathematical scientists, over 70% are employed at for-profit businesses compared to only 30% for biological, agricultural, environmental and life scientists. Hence, depending on the field of study, the distribution of employment outcomes can vary dramatically.

3.1 Academia

The academic employment sector considered here consists of four-year colleges, universities, and university affiliated research institutes (UARI’s). STEM graduates at the bachelor’s level are typically employed as research assistants, research associates or technicians. Master’s
level graduates are predominantly employed as research associates and staff scientists, or instructors or lecturers at teaching institutions. The minimum requirement for a tenure-track professor position is a PhD, with many positions now even requiring one or more postdoctoral appointments (postdocs) depending on the field. In the academic employment sector, the author has found no literature proclaiming a shortage of STEM graduates. On the contrary, there are plenty of articles written about the lack of permanent faculty positions causing young PhDs to take low-paying temporary positions as postdocs and adjunct faculty.

Many students enter into doctoral programs with the intention of climbing the academic ladder and obtaining tenure as a professor. But in many fields, the positions simply do not exist. While the number of PhDs has been steadily climbing, the number of professor positions have remained constant except in the biomedical sciences and computer sciences (National Science Board, 2014). From Figure 3-2, we can see that while the number of PhDs has increased, the number in tenure-track positions has stayed almost constant.

To examine the production of PhDs for the academic job market, Larson et al. (2013) defined the concept of $R_0$ for academia. In demography, $R_0$ is defined as the mean number of baby girls that a typical newly born baby girl will have in her lifetime. Neglecting infant
Figure 3-2: Number of PhDs age 35-or-younger has increased far more than the number who are in tenure-track positions. Source: Teitelbaum (2007b).

deads, if $R_0 > 1.0$, then the population will grow over time. For academia, $R_0$ was defined to be the mean number of new PhDs that a typical tenure-track faculty member will graduate during his or her academic career. When $R_0 = 1.0$, each professor, on average, graduates one new PhD that can replace him or her. However, if we consider that the number of faculty slots has remained almost constant, $R_0 > 1.0$ means that there are more doctorates than existing faculty positions.

Using the same methodology, we estimated $R_0$ for all fields in the U.S. (average career duration was assumed to be 20 years, as in Larson and Diaz (2013)). We use 2012-2013 data from the College and University Professional Association for Human Resources (CUPA-HR), which reports the number of tenured and tenure-track faculty at 794 institutions in the U.S. and data from the Integrated Postsecondary Education Data System (IPEDS), which has the number of PhDs awarded in 2012 for those institutions. By looking at $R_0$, we can gain a sense of the competitiveness for tenure-track position across different disciplines. Disciplines are grouped by CIP-code, a taxonomic scheme devised by the U.S. National Center for Education Statistics to track fields of study. Figure 3-3 shows the calculated $R_0$'s, which

---

1While only 294 of these 794 institutions had doctoral programs, the number of faculty used in the $R_0$ calculation was for all institutions, not just those with doctoral programs, since these are still tenured and tenure-track faculty positions.

2Disciplines were only included if there was data available for both the number of PhDs and faculty.

---

35
have tremendous variation across the broad disciplines.

Figure 3-3: $R_0$ for 794 U.S. institutions by CIP-code, indicating the heterogeneity across 30 different disciplines. Author’s calculations. Data sources: CUPA-HR and IPEDS. See Appendix B for full list of CIP codes and descriptions.

Table 3.1 shows the $R_0$'s for STEM disciplines (not including social sciences). A high $R_0$ indicates that more doctorates are competing for tenured and tenure-track faculty slots, provided that the number of positions remain constant. For example, an $R_0 = 6.9$ indicates that a tenure-track position is only available for 14% (1 out of 6.9) new doctorates in engineering. There are also many fields with $R_0$'s close to 1, these are generally fields that are less research-oriented such as Visual and Performing Arts or Legal Professions and Studies, and not related to STEM. All the STEM fields have an $R_0 > 1$, indicating that there are more doctorates eligible for academic positions than openings.

Sauermann and Roach (2012) studied the preferences of science PhD students ($n= 4,109$) and found that the majority of them considered a faculty research career as an “extremely attractive” career path. Presently, faculty openings frequently attract hundreds of qualified applications (Benderley, 2010). Only a lucky few go directly from graduate school to a
Table 3.1: $R_0$'s for STEM Disciplines

<table>
<thead>
<tr>
<th>STEM Disciplines</th>
<th>$R_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>3.1</td>
</tr>
<tr>
<td>Computer and Information Sciences</td>
<td>3.4</td>
</tr>
<tr>
<td>Engineering</td>
<td>6.9</td>
</tr>
<tr>
<td>Engineering Technologies</td>
<td>2.3</td>
</tr>
<tr>
<td>Biological and Biomedical Sciences</td>
<td>4.0</td>
</tr>
<tr>
<td>Mathematics and Statistics</td>
<td>1.5</td>
</tr>
<tr>
<td>Physical Sciences</td>
<td>3.1</td>
</tr>
<tr>
<td>Science Technologies/Technicians</td>
<td>7.5</td>
</tr>
</tbody>
</table>

tenure-track faculty position. In 2010, less than 15% of new PhDs in science, engineering, and health-related fields found tenure-track positions within 3 years after graduation (National Science Board, 2014). The majority who want an academic career join academia as postdocs or adjunct faculty, hoping to vie for a tenure-track faculty position in the future. An American Association of University Professors' survey found that the salary for adjunct faculty would range from $18,000 at associate's degree colleges to around $30,000 at private doctoral universities for a full course load (Curtis and Thornton, 2013). The median salary for a postdoc in a science, engineering, or health field was $43,000 in 2010 (National Science Board, 2014). Looking at it from an economic perspective, the best indicators of labor shortages are wages. When a particular kind of worker is scarce, employers compete by increasing salary offerings. Thus, these characteristics suggest that we have a glut of well-educated and highly-skilled doctorates, as they are in low-paying positions within academia.

These findings corroborate with many others in the literature. Michael S. Teitelbaum (2007a), VP of the Sloan Foundation, highlighted the poor prospects for recent doctorates and postdocs. The RAND Corporation (2004a) pointed out that the length of postbaccalaureate study for the biosciences has increased considerably from between seven to eight years, to between nine and twelve, and that many graduates are unable secure stable employment with tenure until their late thirties. This sentiment was further substantiated in a National Research Council Report (2005), *Bridges to Independence*, which focused on the poor state of biomedical research careers and urged immediate reform to enhance the quality of training and foster opportunities for young researchers to conduct independent research. While this
academic surplus started out in the biosciences, it has now extended to encompass many STEM fields such as astronomy, meteorology and high-energy physics (Benderley, 2010).

In the academic employment sector, the author has found no evidence of any shortages, whereas there is a significant mismatch between supply of doctorates who want an academic career and the availability of tenure-track faculty positions. While the degree of mismatch varies according to the discipline, we have queues of passengers waiting for taxis for almost all STEM-related faculty positions. This is a clear manifestation of Case 2, a STEM surplus.

3.2 Government

The government employment sector considered in this section consists of the different branches of civilian government such as the Department of Defense (DOD) and National Laboratories, the U.S. Air Force, but also defense and aerospace contractors such as Lockheed Martin and Boeing which require security clearances. The main concerns within the community can be generalized into six areas: i) concern regarding K-12 STEM pipeline, ii) decline in student interest in STEM, iii) inadequate federal and state level funding for the education system, iv) decline in incentives to pursue a STEM career, v) slow growth or decline in the number of U.S. citizens or permanent residents in advanced degrees, and vi) an aging workforce (National Research Council, 2010). As this thesis primarily examines the supply and demand of STEM degrees rather than the STEM pipeline, this section will focus on the last two areas of concern: U.S. citizens with advanced degrees and an aging workforce.

3.2.1 U.S. Citizen or Permanent Residents with STEM Degrees

The International Traffic in Arms Regulations dictate that information and material related to defense and military related technologies may only be shared with U.S. citizens unless an exemption is used. This restriction means that employees must be U.S. citizens, and in some cases, must only be single-citizenship U.S. citizens. While in academia and the private sector, foreign nationals can generally be brought in to bridge skill gaps, for the government and defense-related contractors, this is currently not an option in many areas.

At the bachelor’s level, supply of U.S. citizen and permanent resident STEM graduates
has been consistently increasing in the natural sciences. However, for engineering, while there has been steady growth, it has not approached the same level as 1985 (National Research Council, 2010). Similarly, at the master’s level, there has been stable growth in the number of STEM degrees for U.S. citizens and permanent residents (National Research Council, 2010). But according to the National Research Council Committee’s calculations (2010), there was a 5.5% decrease in the number of doctoral graduates eligible for security clearances between 2000 and 2005. Hence, there was concern within the community as to whether this trend would continue and cause a STEM crisis in the future.

The National Research Council Committee (2010) states that the Air Force had a robust supply of STEM-degreed personnel to meet its recruiting goals for STEM positions, with a few exceptions. The Air Force Personnel Center (AFPC) found manning gaps in electrical engineering, operations research, quantitative psychology, physics, nuclear engineering, and systems engineering. Of specific concern to the AFPC was graduates with advanced degrees. The Aeronautical Systems Center Commander also identified shortages in areas such as electromagnetics, structures, software, reliability and maintainability and manufacturing engineers.

Similarly, another National Academy of Sciences Committee (2012b) charged with identifying the needs for the U.S. DOD and U.S. Defense Industrial base found that DOD representatives almost unanimously stated that there currently is not a STEM workforce crisis, but there are specific areas where needs are not being met. For example, there were 800 funded positions that were open for 90 days or more for systems engineers and other STEM workers, as well as opportunities for cybersecurity and intelligence professionals. Additionally, the committee found that traditional disciplines such as corrosion engineering were not being integrated into bachelor’s degree programs for materials science engineering and related engineering fields, leading to an inadequate background in corrosion engineering principles and practices. The aerospace and defense industry have also experienced difficulty in hiring mechanical engineers, systems engineers, and aerospace engineers.

These sentiments were generally echoed in the interviews we conducted. One participant, a recruiting manager for a research institute said that hiring for bachelor’s level was relatively easy, but hiring for advanced degrees proved more challenging because of skillset...
mismatches\textsuperscript{3}. He noticed that while there were a lot of applicants from mechanical, aeronautical and bioengineering disciplines, there were also shortages for electrical engineers at the doctorate level. An interesting note is that because these engineering and science graduate programs all required advanced math, at times there were transferable skills across disciplines. One example he provided was that a biological engineer specializing in biomedical imaging was hired for a role in radar imaging. Despite the vastly different domains, the underlying mathematics and physics were the same. Software development skills at all degree levels were also in high-demand, remarking that the advancements in technology has caused a shift where there is an older generation of “traditional engineers” and a younger generation that knows how to code, in addition to traditional engineering skills.

Another recruiting manager for a research institute also found difficulties in hiring for advanced degrees in computer sciences and computer engineering\textsuperscript{4}. Due to budget stipulations, their salaries could not compete with those in the private sector for talent. A significant factor was also the location of the position. A position located in Washington D.C. would attract 200 applications within a week, while a comparable position in Kansas would attract only 14.

A hiring manager for a large government contractor, found significant shortages in hiring for doctorates in fields such as nuclear engineering, materials science, and thermohydraulic engineering\textsuperscript{5}. While they only require a dozen or so of each, the supply of the U.S. citizens with doctorates in these fields is small. In order to fulfill their hiring needs, they started programs to sponsor doctorate education in these fields. In addition to experiencing these consistent shortages, there were also transient shortages. For example, for the past two to three years, they have had a shortage of electrical engineers. On the other hand, they have found a consistently high supply of mechanical engineers.

An engineering startup company recruiter said that they had problems finding materials science doctorates who were U.S. citizens\textsuperscript{6}. While they received dozens of applicants from qualified foreign nationals, the government funding required U.S. citizenship, which made

\textsuperscript{3}Research Institute A, primarily involved in U.S. government projects that require U.S. citizenship
\textsuperscript{4}Research Institute B, primarily involved in U.S. government projects that require U.S. citizenship
\textsuperscript{5}Engineering Company A, government contractor that requires U.S. citizenship, no dual citizenship holders
\textsuperscript{6}Engineering Startup
recruiting difficult.

These anecdotal accounts generally corroborate our findings from literature. The one exception is that our study participants have had no difficulty in hiring mechanical engineers, but this may suggest an area where there is sometimes a shortage and sometimes a surplus, or Case 3, a balanced market. Overall, there is ample supply of bachelor’s levels graduates, but hiring for degrees that require advanced degrees in certain areas can be challenging. While there seems to be no overarching STEM crisis at the moment, there are specific disciplines which are lacking in doctorates due to citizenship restrictions or high demand in general. Some of these are influenced by location or are simply transient, but other STEM positions require concerted effort to meet hiring needs.

3.2.2 Aging Workforce

Compounding the problem of stagnating numbers of U.S. citizens obtaining advanced degrees in STEM is the aging of the current workforce. At the Air Force Research Laboratory, forty percent of civilian scientists and engineers are approaching retirement eligibility (National Research Council, 2010). At DOD, the age distribution for the STEM workforce is bimodal, with a new younger cohort, and an older cohort of which a large fraction are eligible to retire within the next few years, see Figure 3-4 and Figure 3-5. These problems are mirrored in the defense and aerospace industry. In 2011, twenty percent of the workforce was eligible to retire at the Boeing Company, and twenty percent more would be in 5 years’ time (National Academy of Sciences, 2012b). Yet ultimately, the committee found that because DOD and its industrial contractor’s STEM workforce needs are relatively modest (only around 2% of the total U.S. STEM workforce) the incoming supply should be sufficient, except for specialized areas such as cybersecurity and certain intelligence fields. In 2011, Rick Stephens, the VP for Human Resources at the Boeing Company said that the company would expect to fill 16,000 STEM positions, for which it would anticipate 2.5 million resumes (National Academy of Sciences, 2012b). The issue at hand was not the quantity of the supply, but rather the quality and skillset match.

In the government and government contractor employment sector, the author has found no evidence of widespread STEM shortages, similar to the RAND Corporation study con-

Figure 3-5: Retirement eligibility of selected occupational groups in the DOD civilian STEM workforce. Source: National Academy of Sciences (2012a).

Conducted in 2004 (RAND Corporation, 2004b). However, there are shortages in specific areas such as cybersecurity, intelligence, electrical engineering, and systems engineering. There are also transitory surpluses and shortages in areas such as mechanical engineering. Furthermore, while there may be shortages at the doctorate level due to security clearance requirements, they represent a very small fraction of total STEM employment, see Figure 3-6. To address these hiring concerns, programs were created to sponsor employees for advanced education (National Academy of Sciences, 2012b). For example, the Boeing company has 3,000 personnel attending school full-time and the DOD has a Science, Mathematics and Research for Transformation (SMART) Scholarship for Service Program that sponsors full
undergraduate or graduate tuition in exchange for employment post-graduation.

![Diagram](image)

**Figure 3-6:** Highest degree attained for DOD civilian STEM workforce, 2001-2011. Source: National Academy of Sciences (2012a).

### 3.3 Private Sector

Much of the literature regarding the "STEM Crisis" emanates from concerns of shortages or surpluses in the private sector STEM labor market; however, it is generally talked about in broad terms, referencing the entire STEM workforce as a whole. For example, the PCAST report called for an additional 1 million STEM degrees over the next decade (President’s Council of Advisors on Science and Technology, 2012). Similarly, there are many studies that refute the claim that there are STEM shortages at the aggregate level, but mention that there are shortages in specific fields (Lowell and Salzman, 2007, Teitelbaum, 2007b). But which degrees and at which degree levels are actually in demand? This section will contain a literature review of the studies that have pointed out specific areas of need or surplus, which will be supplemented by interview responses from our study.

Wadhwa et al. (2007) surveyed 58 U.S. corporations engaged in outsourcing and found no indication of a widespread shortage of engineers. The Economic Policy Institute (EPI) assessed the employment trends of the information technology (IT) workforce and found that
U.S. colleges graduate around 50% more students than are hired into those fields each year (see Figure 3-7) (Salzman et al., 2013). They also examined the reasons for not pursuing a job directly to their degree. For computer science graduates, 50% said that it was because career prospects were better elsewhere, and roughly a third said they could not find a job in IT. For engineering graduates, a third cited career prospects were better elsewhere and another third said that jobs were not available. Wages for IT workers have stagnated since 2000, with the exception of Silicon Valley. From their analysis, it appeared that for bachelor’s level graduates in IT, there is no shortage of supply.

![Figure 3-7: Occupational field of STEM college majors one year after graduation, 2009. Source: Salzman et al. (2013).](image)

International Communications Research conducted a survey with 150 talent recruiters at Fortune 1000 STEM and non-STEM companies. They found that only around half of the respondents said that can find an adequate numbers of qualified job candidates with either two-year or four-year STEM degrees in a timely manner (International Communications Research, 2013). Of those who said that they could not find adequate candidates, the vast majority believed there was a shortage of qualified candidates. In particular, the manufacturing industry said that it had difficulty finding adequate numbers of four-year
STEM degree holders. A 2011 survey of manufacturers found that as many as 600,000 jobs remained unfilled due to lack of qualified candidates for technical positions requiring STEM skills, primarily in skilled production (machinists, operators, craft workers, distributors and technicians) (The Manufacturing Institute and Deloitte, 2011). There is concern that very few people are pursuing employment in the skilled trades (Wright, 2013).

3.3.1 Shortages

Looking to anecdotal accounts, there have been many specific areas identified as having a shortage of STEM talent. Frenzel (2013) identified shortages in analog/linear and RF/microwave design engineers, and skilled programmers. The unemployment rate for software developers has been dropping in recent years, from 4% in 2011 to 2.8% in 2012 and down to 2.2% in the first quarter of 2013, indicating that jobs for software developers are on the rise (Thibodeau, 2013). Rothwell (2012), a senior research analyst at Brookings, found that in 2010, there were seven job openings in computer occupations for every graduate from a relevant computer major by analyzing Conference Board's Help-Wanted Online Series. Wanted Analytics, which aggregates job listings from all over the web, reported in 2013 that help-wanted ads for software developers are up 120% over the previous year (Lombardi, 2013). The recent big data trend has also sparked demand for data scientists in all areas from health care to retail (de Lange, 2013).

Due to increasing energy prices and new technologies for domestic extraction for oil and gas, petroleum engineers are now in high demand, even though it was a position that was unattractive and declining throughout the 1980s and 1990s (Porretto, 2007, Wadhwa, 2011, Teitelbaum, 2014).

From our surveys with recruiters, we also found software development skills to be the most in demand. Experienced mobile application developers were especially coveted7. In many cases, whether or not a candidate had a bachelor's degree in the area did not matter. Companies were looking for candidates with hands-on experience in software development

---

7Media Company A
through hack-a-thons, extracurricular projects, and internship experiences. While some recruiters did mention that there were difficulties in hiring for computer engineering and process engineering doctorates, these represented only a small fraction of positions within the company. The majority (95%) of their STEM positions could be filled by candidates at the bachelor's or master's level.

3.3.2 Surpluses

Similarly, certain areas have had a surplus of STEM talent. Most notably, biomedical doctorates. An NIH blue-ribbon panel found that an increasing number of biomedical doctorates were working in science-related occupations that did not involve conducting research and even occupations that did not require graduate training in science (National Institutes of Health, 2012). Chemistry and biomedical graduates have also taken a hard hit due to the downsizing and offshoring of biotechnology, chemical and pharmaceutical industries (Cyranoski et al., 2009, Bloom, 2011). Since 2000, U.S. pharmaceutical companies have cut 300,000 jobs (Vastag, 2012). Due to the downsizing, the unemployment rate among chemists in 2012 stood at 4.6%, the highest in 40 years (Morrissey, 2012). Among young PhDs, the situation is even worse, where only 38% of newly minted chemist doctorates are employed in full-time, non-postdoc positions in 2011, see Table 3.2 for more detail regarding employment outcomes of recent graduates (Morrissey, 2012). New chemical engineer doctorates fared better, with a full-time non-postdoc employment rate of 61%. One recruiter said he found that many chemical engineering college graduates were seeking employment in software development.

In 2010 and 2011, the unemployment for electrical engineers held at 3.4%, but spiked to 6.5% in the first quarter of 2013 (Thibodeau, 2013). While recruiters in the government and government contractor space had concerns with hiring electrical engineers, these concerns did not surface from our survey with recruiters in the private sector, indicating that the hiring challenge in the government space is probably due to the U.S. citizenship requirement.

---

8Media Company A
9Engineering Company B
10IT Company D
11Engineering Company B
12IT Company C
13IT Company A
Table 3.2: Employment status of new graduates in chemistry and related fields, in percent. Source: Morrissey (2012).

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bachelor’s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full-time</td>
<td>40</td>
<td>42</td>
<td>43</td>
<td>40</td>
<td>32</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Permanent</td>
<td>31</td>
<td>34</td>
<td>33</td>
<td>31</td>
<td>23</td>
<td>24</td>
<td>23</td>
</tr>
<tr>
<td>Temporary</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Part-time</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>7</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Permanent</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Temporary</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Graduate/professional school</td>
<td>44</td>
<td>44</td>
<td>40</td>
<td>41</td>
<td>46</td>
<td>46</td>
<td>41</td>
</tr>
<tr>
<td>Not employed</td>
<td>12</td>
<td>10</td>
<td>11</td>
<td>14</td>
<td>15</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Seeking</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Not seeking</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Master’s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full-time</td>
<td>50</td>
<td>52</td>
<td>54</td>
<td>49</td>
<td>43</td>
<td>47</td>
<td>48</td>
</tr>
<tr>
<td>Permanent</td>
<td>45</td>
<td>44</td>
<td>48</td>
<td>41</td>
<td>38</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>Temporary</td>
<td>5</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Part-time</td>
<td>9</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Permanent</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Temporary</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Graduate/professional school</td>
<td>30</td>
<td>34</td>
<td>34</td>
<td>35</td>
<td>30</td>
<td>31</td>
<td>22</td>
</tr>
<tr>
<td>Not employed</td>
<td>11</td>
<td>9</td>
<td>6</td>
<td>10</td>
<td>18</td>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>Seeking</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>7</td>
<td>15</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>Not seeking</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

| PhD                  |      |      |      |      |      |      |      |
| Full-time            | 44   | 41   | 50   | 53   | 45   | 44   | 38   |
| Permanent            | 39   | 37   | 46   | 51   | 40   | 38   | 33   |
| Temporary            | 5    | 4    | 3    | 3    | 5    | 7    | 5    |
| Part-time            | 2    | 2    | 2    | 2    | 3    | 2    | 4    |
| Permanent            | 0    | 1    | 1    | 1    | 0    | 0    | 0    |
| Temporary            | 2    | 1    | 2    | 2    | 3    | 1    | 4    |
| Postdoc              | 45   | 49   | 41   | 37   | 44   | 45   | 47   |
| Not employed         | 9    | 8    | 7    | 7    | 9    | 9    | 12   |
| Seeking              | 6    | 6    | 5    | 4    | 7    | 6    | 9    |
| Not seeking          | 3    | 2    | 2    | 3    | 2    | 3    | 3    |

Notes: Employment status of all respondents as of October each year.
Respondents listed by highest degree received.
Numbers may not sum to 100%, because of rounding.
Because the unemployment rate for STEM doctorates is generally low, a more useful indicator of job market strength is to look at the number who accept potentially permanent positions compared to the number who accept postdocs. A significant portion of physics doctorates are accepting postdocs and other temporary positions (60% in 2010 compared to 40% before the dotcom bust), indicating that the demand for physics doctorates is not high in the economy (see Figure 3-8) (Anderson and Mulvey, 2013).

![Initial employment of physics doctorates in the U.S., 1979 through 2010. Source: Anderson and Mulvey (2013).](image)

**Figure 3-8:** Initial employment of physics doctorates in the U.S., 1979 through 2010. Source: Anderson and Mulvey (2013).

### 3.3.3 Spatial Differences

Geographically, there are also differences in the labor markets for STEM workers. For example, software developers are in much higher demand in California, Washington and New York, which is reflected in their higher wages (see Figure 3-9). This trend is seen across different STEM occupations and areas of demand vary. Petroleum engineers, for example, are clustered in Texas and Oklahoma. One recruiter mentioned that they specifically relocated their business to the Boston area so that they could have access to the talent pool in the vicinity and that it improved their recruitment\(^\text{14}\). A recruiter for a company located in

\(^{14}\)IT Company E
Connecticut said that one of the primary challenges in hiring software developers is the location of the office: many qualified candidates were reluctant to relocate to Connecticut\textsuperscript{15}.

![Map of annual mean wage of software developers by state](image)

Figure 3-9: Annual mean wage of software developers, applications, by state, May 2013. Source: Bureau of Labor Statistics (2013).

3.4 Summary

Across all the different disciplines, yes, there is a "STEM Crisis" and no, there is not a "STEM Crisis". It depends on where you look.

For most doctorates, we have a surplus, especially for tenure-track positions in academia. The exceptions are certain fields within industry such as petroleum engineering, process engineering and computer engineering, or within the government space: nuclear engineering, materials science, and thermohydraulic engineering. However, the percentage of positions for doctorates is small compared to the general STEM workforce. Academia tends to absorb the doctorates that are unable to find positions in industry into postdoc positions. At the

\textsuperscript{15}Media Company A
bachelor’s and master’s levels, there is consistent demand for roles in software development, and in high growth areas such as mobile app development, data science and petroleum engineering. There is also demand below the bachelor’s level, as the manufacturing industry requires workers in the skilled trades, such as machinists and technicians. Hence, we have a heterogeneous mixture of queues: some have a queue of workers, some have a queue of unfilled positions, and some shift between a queue of workers and a queue of unfilled positions.
Chapter 4

Policy Discussion

The recent wave of concern about an impending STEM crisis arose primarily due to the National Academy of Sciences' report (2007), *Rising Above the Gathering Storm*, which has formed the basis for the America COMPETES Act. This is by no means the first time that alarms have been raised regarding shortages in the STEM workforce.

In the late 1950s, the surprise launch of Sputnik by the Soviet Union prompted the U.S. Congress to enact the National Defense Education Act of 1958 (NDEA). “To meet the [...] educational emergency”, the act was designed to strengthen and reform American education at all levels to “insure trained manpower of sufficient quality and quantity to meet the national defense needs of the United States” (*National Defense Education Act of 1958, Pub. L. No. 85-864, 72 Stat. 1002, 1958*). One billion was injected over a 4-year period to provide 40,000 loans, 40,000 scholarships, and 1,500 graduate fellowships (Flemming, 1960). At the same time, the elevated federal funding for R&D prompted a wave of demand for scientists and engineers, and thus the STEM shortage indeed reflected reality at the time. However, just over a decade later, there were more newly trained scientists and engineers than jobs available in the mid-1970s (RAND Corporation, 2004a).

In the 1980s, the concern over the supply of scientists and engineers surfaced again. The National Science Foundation (NSF) predicted that there would be impending shortfalls on the order of 675,000 scientists and engineers by 2006 (Holden, 1989). The shortage never materialized. On the contrary, a statement by Michael S. Teitelbaum (2003) claimed that there was actually a growing surplus of scientists and engineers shortly thereafter.

The “STEM Crisis” dialogue has remained at the forefront of policy discussion throughout
the 2000s. Notable reports have been published by the National Science and Technology Council (2000) and National Science Board (2003 amongst others. They called for a boost in the number of US citizens pursuing science and engineering studies and careers, based on concerns such as:

- U.S.’s weak K-12 education system, particularly its inadequacies in science and mathematics as measured by global assessment tests such as TIMSS.
- A declining level of interest in STEM fields because of their relative difficulty.
- A decreasing proportion of U.S. Citizens pursuing STEM fields.

To address these concerns, the Gathering Storm Committee developed a set of policy recommendations, which can be grouped into the following areas:

- Increasing federal investment in basic science and engineering research.
- Drawing in the best and brightest, i.e., increasing the number and proportion of U.S. citizens in higher education, as well as attracting international students.
- Enhancing K-12 science and mathematics education.
- Encouraging innovation in the U.S. through improving the patent system and providing economic incentives.

While some of the points are less contentious, seemingly benign recommendations such as increasing federal investment in basic science and engineering research and attracting more STEM students can adversely affect the STEM workforce if the demand for STEM workers is not present in the labor market. Some of these impacts are discussed below.

4.1 Unintended Consequences of Rapid Funding Increases

Let us first examine the effects of a rapid increase in federal investment for basic science and engineering research. Under the current funding system, principal investigators propose and carry out research projects, which are administered by universities. Government relies
upon universities to conduct the research, and universities rely on the government by taking a portion of each grant for operations. This system also supports graduate education by employing graduate students as researchers, who are trained with the intention of becoming future faculty members and winning grants of their own.

The interdependent nature of the higher education system and grant allocations causes the system to be extremely sensitive to fluctuations in funding levels at the graduate level, as shown by Larson et al. (2012). The rapid injection of new grants creates a substantial short-term demand for additional doctoral students and postdocs to perform the research. This in turn produces a larger pool of well-educated STEM workers, but does not address their long-term career prospects. The growth in funding does not necessarily tie in to an increase of the number of tenure-track faculty positions that these doctorates and postdocs are trained to become. As seen in Chapter 3, the number of tenure-track faculty positions has stayed relatively flat over the past 30 years. Moreover, these doctorates go on to compete for the same set of grants, and generate a steady stream of new doctorates themselves (recall the concept of $R_0$), further increasing the competition for grants and reinforcing the supply of STEM workers. Thus, unless the number of faculty positions and research funding increase exponentially over time, this system cannot be sustained.

This phenomenon was apparent when NIH doubled its budget between 1998 and 2003. Due to this budget increase, the number of applications almost doubled over the same period. It was observed that the median age of a PhD researcher’s first research grant was increasing, meaning that the awards are shifting towards older rather than younger researchers (National Research Council, 2005). In 1980, researchers under the age of 40 received over half of the competitive research awards. The share fell to just 17% for the same age group in 2003. The increased competition for grants and faculty positions has led to the fear that prospective students will choose alternative paths, and that researchers are led to pursue more conservative projects rather than high-risk, high-reward research.

For the system to be sustainable and beneficial to the STEM workforce, the research funding increase should occur slowly and be sustained over a long period (Larson et al., 2012). Furthermore, this additional influx of STEM doctorates needs to be met by an appropriate level of demand. As seen in Chapter 3, doctorates are currently taking low-
paying jobs as postdocs or adjunct faculty because it is increasingly difficult to find tenure-track positions in academia. Unfortunately, creating additional tenure-track positions only proliferates the number of doctorates in the future and further worsens the situation because of the reinforcing feedback loop. Hence, when action is taken to increase the supply of doctorates by injecting additional research funding into the system, balancing policies that address the demand-side of the STEM doctorate workforce need to be carefully crafted simultaneously.

4.2 Attracting More Students to STEM

Broad claims that there is an impending shortage of STEM professionals can be misleading when certain STEM job segments are currently oversupplied. At the same time, our analysis has shown that there are many areas where there is a clear demand for STEM professionals, such as software development, petroleum engineering, and doctorates with U.S. citizenship in certain engineering fields. STEM professionals span across hundreds of occupations, with varying requirements for degree level and citizenship.

Furthermore, STEM can be regarded in a broader sense, as a manner of thinking and doing rather than a set of occupations. Much like how traditional literacy encompasses an ability to identify, understand and communicate with written materials, STEM-literacy can be thought of as a set of core cognitive competencies such as logical reasoning, analytical thinking, and problem solving skills. STEM education does not necessarily apply to only those who plan to pursue careers as scientists and engineers, competency in STEM can be for everyone (Larson, n.d.). We found that STEM graduates were not only hired into STEM roles, but also in areas outside of STEM such as consulting, investment banking, and law. This corroborates with the findings of the Georgetown Center for Education and Workforce’s Report on STEM, which suggest that the knowledge and skills acquired from a background in STEM are not only applicable to traditional STEM domains, but widely sought after in other occupations as well (Carnevale et al., 2011).

Also, as technology continues to advance and permeate our workspace, the positions and job requirements for workers will continue to change. For example, modern automobiles
have evolved to be extremely complex systems: even a low-end vehicle is equipped with 30 to 50 electronic control units to execute software code that powers everything from the stereo volume to air bags (Charette, 2009). As a result, automotive master mechanics need to use computerized devices and require an understanding of these systems. This shift towards highly-skilled technicians with STEM knowledge is occurring across the manufacturing and construction industry (Rothwell, 2013). The Brookings Institution found that around 13 million U.S. jobs require a high level of knowledge in any one STEM field, and are available to workers without a four-year college degree (Rothwell, 2013).

![Figure 4-1: Projected New Jobs in STEM Occupations, 2008-2018. Source: Munce and Fraser (2013) based on BLS data.](image)

According to the Bureau of Labor Statistics, STEM occupations are projected to grow by around 1 million jobs in ten years over 2008 employment levels (see Figure 4-1 for distribution of job growth) (Munce and Fraser, 2013). To meet the demand for more STEM skills, appropriate policies are required to attract more students to STEM. Top-down policies need to be focused on specific areas of demand in order to address the shortage concerns as well as to avoid exacerbating oversupply in areas where there currently is no shortage. Also, policies need to provide incentives to attract students to STEM. For example, the New York State STEM Incentive Program provides college scholarships to top-performing high school seniors who pursue a career in any STEM field (Chapman, 2014). A bottom-up approach to bridging the gap is to have companies identify areas of need and sponsor students and/or
employees for higher education. Companies like Boeing and government agencies such as DOD have created specific programs that sponsor employees for higher education to address deficiencies in their pipeline of STEM workers. This has proven to be an effective mechanism to draw talent that pertains specifically to the needs of the employer.

4.3 Conclusion

This thesis draws upon a variety of data sources such as professional science and engineering societies, the National Science Foundation, literature reviews and anecdotal accounts to understand the supply and demand landscape for the STEM labor market. It presents a first cut at identifying disciplines and degree levels that are in demand or oversupplied. A clearer picture of the supply and demand of the STEM workforce will require better data and consistent monitoring of both employer requirements and STEM worker availabilities.

The taxi-cab queuing model was introduced as a metaphor for the STEM labor market. Depending on the STEM job segment, we can either have a queue of positions waiting to be filled (taxis) or we can have a queue of STEM workers waiting for jobs (passengers). The characteristics of the queue depend on different factors: rate of job turnover (taxi service rate); STEM worker arrival rate (passenger arrival rate); number of positions available (taxis in the fleet); location; degree level (type of taxi); and citizenship. The model also highlights the probabilistic nature of the supply and demand market. Random fluctuations can cause job segments that traditionally have a shortage of workers to have a surplus and vice versa. While we currently lack the data to operationalize the model, it presents a novel approach to characterizing the variation across STEM job segments.

To answer our central question: is there a "STEM Crisis" or a "STEM Surplus"? The answer is both. From our analysis, we found that:

- The STEM labor market is heterogeneous. There are both queues of STEM workers and queues of positions depending on the particular job market segment.

- In the academic job market, there is no noticeable shortage in any discipline. In fact, there are signs of oversupply in many disciplines (e.g. biomedical sciences, physical sciences) for tenure-track faculty positions.
• In the government job sector, there are shortages for certain STEM disciplines at the PhD level (e.g. materials science engineering, nuclear engineering) and in general (e.g. systems engineers, cybersecurity and intelligence professionals) due to the U.S. citizenship requirement. Oversupply was noticed in biomedical engineers at the PhD level, and transient shortages in electrical engineers and mechanical engineers.

• In the private sector, there is high demand for software developers, petroleum engineers, data scientists, skilled trades; an abundant supply of biomedical, chemistry, and physics doctorates; and transient shortages/surpluses for electrical engineers.

• Location of the position affects hiring difficulty.

Policies that try to solve shortages by increasing overall supply of STEM graduates through attracting students or increasing federal funding may not improve the overall STEM workforce, and may even exacerbate any mismatches between supply and demand. As our society relies further on technology for economic development and prosperity, the vitality of the STEM workforce will continue to be a cause for concern.
Appendix A

Taxicab Queueing Model Derivation

In steady state, the flow going into each state must be equal to the flow going out of each state. Thus, we have the following system of equations for the balance of flows. We write all of the equations in terms of \( \pi_0 \).

For states \(-N\) to 0:

\[
\lambda \pi_{-1} = N\mu \pi_0, \quad \pi_{-1} = N\frac{\mu}{\lambda} \pi_0 \quad \text{(A.1)}
\]

\[
\lambda \pi_{-2} = (N-1)\mu \pi_{-1}, \quad \pi_{-2} = N(N-1) \left(\frac{\mu}{\lambda}\right)^2 \pi_0 \quad \text{(A.2)}
\]

\[
\ldots
\]

\[
\lambda \pi_{-k} = (N-k+1)\mu \pi_{-k+1}, \quad \pi_{-k} = \frac{N!}{(N-k)!} \left(\frac{\mu}{\lambda}\right)^k \pi_0 \quad \text{(A.3)}
\]

\[
\ldots
\]

\[
\lambda \pi_{-N} = 2\mu \pi_{-N+1}, \quad \pi_{-N} = N! \left(\frac{\mu}{\lambda}\right)^N \pi_0 \quad \text{(A.4)}
\]
For states 1 to $\infty$:

\[ \lambda \pi_{(n)} = N \mu \pi_{(1)}, \pi_{(1)} = \frac{1}{N} \frac{\lambda}{\mu} \pi_{(0)} \]  
(A.5)

\[ \lambda \pi_{(1)} = N \mu \pi_{(2)}, \pi_{(-2)} = \frac{1}{N^2} \left( \frac{\lambda}{\mu} \right)^2 \pi_{(0)} \]  
(A.6)

\[ \lambda \pi_{(k-1)} = N \mu \pi_{(k)}, \pi_{(k)} = \frac{1}{N^k} \left( \frac{\lambda}{\mu} \right)^k \pi_{(0)} \]  
(A.7)

The probability of being in any one of the states must sum to one:

\[ \sum_{i} \pi_{(i)} = 1 \]  
(A.8)

\[ \sum_{i=0}^{N} \frac{N!}{(N-i)!} \left( \frac{\mu}{\lambda} \right)^i \pi_{(0)} \] is the sum of the probabilities from state $-N$ to 0.

\[ \sum_{i=1}^{\infty} \frac{1}{N^i} \left( \frac{\lambda}{\mu} \right)^i \pi_{(0)} \] is the sum of the probabilities from state 1 to $\infty$.

\[ \sum_{i=0}^{N} \frac{N!}{(N-i)!} \left( \frac{\mu}{\lambda} \right)^i \pi_{(0)} + \sum_{i=1}^{\infty} \frac{1}{N^i} \left( \frac{\lambda}{\mu} \right)^i \pi_{(0)} = 1 \]  
(A.9)

To simplify the expression: $\rho = \frac{\lambda}{\mu}$.

\[ \sum_{i=0}^{N} \frac{N!}{(N-i)!} \left( \frac{1}{\rho} \right)^i \pi_{(0)} + \sum_{i=1}^{\infty} \left( \frac{\rho}{N} \right)^i \pi_{(0)} = 1 \]  
(A.10)

Factoring out constants:

\[ \pi_{(0)} \left( \sum_{i=0}^{N} \frac{N!}{(N-i)!} \left( \frac{1}{\rho} \right)^i + \sum_{i=1}^{\infty} \left( \frac{\rho}{N} \right)^i \right) = 1 \]  
(A.11)

\[ \sum_{i=0}^{N} \frac{N!}{(N-i)!} \left( \frac{1}{\rho} \right)^i \] evaluates to $e^\rho \left( \frac{1}{\rho} \right)^N \Gamma(N + 1, \rho)$.  

60
\[
\sum_{i=1}^{\infty} \left( \frac{p}{N} \right)^i \text{ is a geometric series, which converges to } \frac{\frac{p}{N}}{1 - \frac{p}{N}} \text{ if } |\frac{p}{N}| < 1
\]

\[
\pi(0) \left( e^p \left( \frac{1}{p} \right)^N \Gamma(N + 1, \rho) + \frac{\rho}{N} \frac{e^p}{1 - \frac{p}{N}} \right) = 1
\]  
(A.12)

Where \( \Gamma(a, x) \) is the upper incomplete gamma function.

\[
\pi(0) = \frac{1}{e^p \left( \frac{1}{p} \right)^N \Gamma(N + 1, \rho) + \frac{\rho}{N} \frac{e^p}{1 - \frac{p}{N}}}
\]  
(A.13)

\[
\pi(k) = \begin{cases} 
\frac{N!}{(N-i)!} \left( \frac{\mu}{\lambda} \right)^i \pi(0) & \text{if } -N \leq k \leq 0 \text{ queue of positions} \\
\frac{1}{N^i} \left( \frac{\lambda}{\mu} \right)^i \pi(0) & \text{if } -k > 0 \text{ queue of workers}
\end{cases}
\]  
(A.14)

Using the steady-state probabilities, we can calculate the average length of the queue:

\[
\bar{L}_{employers} = \sum_i i \pi(i) = \sum_{i=0}^{N} \frac{i \cdot N!}{(N - i)!} \left( \frac{\mu}{\lambda} \right)^i \pi(0)
\]  
(A.15)

\[
\bar{L}_{workers} = \sum_i i \pi(i) = \sum_{i=0}^{N} \frac{i}{N^i} \left( \frac{\lambda}{\mu} \right)^i \pi(0)
\]  
(A.16)
Appendix B

$R_0$ Methodology

$R_0$ is defined as the mean number of new PhD’s that a typical tenure-track faculty member will graduate during his or her academic career.

We calculate $R_0$ following the same methodology as in Larson et al. (2013). We use data from the 2012-2013 College and University Professional Association for Human Resources (CUPA-HR) Faculty Survey, which reports the number of tenured and tenure-track faculty at 794 institutions in the U.S. and data from the Integrated Postsecondary Education Data System (IPEDS), which has the number of PhDs awarded in 2012 for those institutions. In the CUPA-HR dataset, the number of faculty includes all types of four-year U.S. institutions, including institutions that do not grant PhD degrees. This gives an estimation of the number of faculty slots available in academia. The average career duration was assumed to be 20 years, as in Larson and Diaz (2013). Only fields with data available for both PhDs and faculty were included in the calculations. While this is a simple model, it gives a sense of the variation in competitiveness for tenure-track faculty positions across different fields.
B.1 2-Digit CIP Codes

01) Agriculture, Agriculture Operations, and Related Sciences.
03) Natural Resources and Conservation.
04) Architecture and Related Services.
05) Area, Ethnic, Cultural, Gender, and Group Studies.
09) Communication, Journalism, and Related Programs.
10) Communications Technologies/Technicians and Support Services.
11) Computer and Information Sciences and Support Services.
12) Personal and Culinary Services.
13) Education.
14) Engineering.
15) Engineering Technologies and Engineering-Related Fields.
16) Foreign Languages, Literatures, and Linguistics.
19) Family and Consumer Sciences/Human Sciences.
22) Legal Professions and Studies.
23) English Language and Literature/Letters.
24) Liberal Arts and Sciences, General Studies and Humanities.
26) Biological and Biomedical Sciences.
27) Mathematics and Statistics.
30) Multi/Interdisciplinary Studies.
31) Parks, Recreation, Leisure, and Fitness Studies.
32) Basic Skills and Developmental/Remedial Education.
33) Citizenship Activities.
34) Health-Related Knowledge and Skills.
35) Interpersonal and Social Skills.
36) Leisure and Recreational Activities.
37) Personal Awareness and Self-Improvement.
38) Philosophy and Religious Studies.
39) Theology and Religious Vocations.
40) Physical Sciences.
41) Science Technologies/Technicians.
42) Psychology.
44) Public Administration and Social Service Professions.
45) Social Sciences.
46) Construction Trades.
47) Mechanic and Repair Technologies/Technicians.
48) Precision Production.
49) Transportation and Materials Moving.
50) Visual and Performing Arts.
51) Health Professions and Related Programs.
53) High School/Secondary Diplomas and Certificates.
54) History.
55) Residency Programs.
Appendix C

Survey Methodology and Results

Talent recruiters are a very difficult group to reach. A total of 18 interviews in-person (14) and telephone (4) were completed with recruiters. For the telephone interviews, recruiters were contacted via email. Recruiter emails were obtained from MIT Career Bridge's website. Telephone interviews had a response rate of 5.4% (4 out of 74). For in-person interviews, recruiters were approached at MIT career fairs, with a response rate of 72% (14 out of 20). Because of the small sample size, and response rate, there is a possibility of self-selection. Recruiters were provided with the information on the following page.
C.1 Consent Form

STEM Workforce Study

You have been asked to participate in a research study conducted by Yi Xue from Engineering Systems Division at the Massachusetts Institute of Technology (M.I.T.). The purpose of the study is to gain a deeper understanding of the state of the labor market of STEM (science, technology, engineering, math) workers. The results of this study will be included in Yi Xue’s Masters thesis. You were selected as a possible participant in this study because you are working with recruitment or career services. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- This interview is voluntary. You have the right not to answer any question, and to stop the interview at any time or for any reason. I expect that the interview will take about 30 minutes.

- You will not be compensated for this interview.

- Unless you give us permission to use your name, title, and / or quote you in any publications that may result from this research, the information you tell us will be confidential.

- I would like to record this interview so that I can use it for reference while proceeding with this study. I will not record this interview without your permission. If you do grant permission for this conversation to be recorded, you have the right to revoke recording permission and/or end the interview at any time.

This project will be completed by June 1, 2014. All interview recordings will be stored in a secure work space until one year after that date. The tapes will then be destroyed.
C.2 Interview Questions

Recruiters were asked to respond to the following questions. Due to privacy and/or time limitations, some of the recruiters only responded to a portion of the questions.

1. What industry does your company belong to?
2. Approximate number of employees?
3. What type of positions do you hire for?
4. Approximate number of openings?
5. Approximately how many hires are recruited from school and how many are professional hires per year?
6. What is the approximate distribution of new recruits (ratio of university recruits to professional hires)? (e.g. 50% new recruits are straight from school)
7. Can you provide an approximate breakdown of the university recruits by degree attainment? (e.g. 50% Masters, 40% Bachelors, 10% PhD)
8. Approximately what percentage of non-technical roles (e.g. management) have STEM (science, technology, engineering, math) degrees?
9. On a scale of 1 to 5 how difficult is it to find employees to fill vacant positions for university hires? (1 being not difficult, 5 being extremely difficult)
10. On a scale of 1 to 5 how difficult is it to find employees to fill vacant positions for professional hires? (1 being not difficult, 5 being extremely difficult)
11. What makes hiring difficult? (Getting applications, not finding the right match, or rejecting offers, etc.)
12. Talk about the difficulty in finding employees to fill positions at the following degree levels: (Less than high-school, High-school, Technical degree, Bachelor's, Master's, PhD, Professional Hire)
13. Are employees expected to learn much of what they need on the job, or should they have sufficient prior knowledge?
14. How long is a typical interview process for a vacant full-time position (in terms of number of interviews and screenings)? Does this vary according to type of position? Has this changed over the years?
15. Do you hire below college level?
16. Besides technical skills, what other skills are important?
17. Do you hire internationals?
18. Where is most of recruiting done? (online/at specific schools)

19. Greatest difficulties when it comes to recruiting?

20. Are their skill or job areas where there’s an internal need, but no graduates have this skill set?

21. Do you have internships? (Interns to full time hire ratio?)

22. Have you found any shifts in the demand for different skills, and what do you expect going forward?

23. Have you noticed a change in difficulty in hiring over the years?

24. Any thoughts on how education can better prepare workers?
## C.3 Survey Results

<table>
<thead>
<tr>
<th>Company Code</th>
<th>Size</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture Company</td>
<td>51-200</td>
<td>No problems hiring architects (slow market). Demand for building scientists and architectural programmers.</td>
</tr>
<tr>
<td>Consulting Company A</td>
<td>110</td>
<td>Hire undergraduates with engineering background for business intelligence roles. No comments on difficulty hiring, new to hiring at schools.</td>
</tr>
<tr>
<td>Consulting Company B</td>
<td>51-200</td>
<td>No notable shortages in hiring. Supply varies over time. Nuclear engineers used to be harder to hire for, now electrical engineers. Difficult to hire nuclear, materials science, thermohydraulic PhDs. Always a lot of mechanical engineers. Can only hire sole U.S. citizenship candidates, significantly limits candidate pool. A lot of engineers retiring soon.</td>
</tr>
<tr>
<td>Engineering Company A</td>
<td>6200</td>
<td>Not too much difficulty hiring for hardware and software roles. Occasionally difficult at PhD level, hard to find match, but not many people hiring.</td>
</tr>
<tr>
<td>Engineering Company B</td>
<td>5000+</td>
<td>Harder to hire for software engineers than electrical and mechanical. Focused mainly on professional hires so far.</td>
</tr>
<tr>
<td>Engineering Company C</td>
<td>300</td>
<td>Much easier to hire in Boston area than New York. Had difficulty filling a PhD position for Materials Science due to US Citizenship requirement</td>
</tr>
<tr>
<td>Engineering Startup A</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Company Code</td>
<td>Size</td>
<td>Comments</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>IT Company A</td>
<td>1500</td>
<td>High demand for software developers. Notice many in chemical engineering applying for software development jobs.</td>
</tr>
<tr>
<td>IT Company B</td>
<td>10000+</td>
<td>Comparatively more difficult to hire network engineers.</td>
</tr>
<tr>
<td>IT Company C</td>
<td>3400</td>
<td>Hard to hire for process engineer PhDs, but limited number of positions.</td>
</tr>
<tr>
<td>IT Company D</td>
<td>9000</td>
<td>Hires primarily software developers, has had medium difficulty hiring. A lot of programs have become more specialized, making hiring easier.</td>
</tr>
<tr>
<td>IT Company E</td>
<td>30</td>
<td>Intentionally located in Boston area to attract local talent. Need very specialized talent (Java developers).</td>
</tr>
<tr>
<td>Law Firm</td>
<td>241</td>
<td>Many applicants from biology, hard to hire for computer and electrical group.</td>
</tr>
<tr>
<td>Media Company A</td>
<td>5000-10000</td>
<td>High demand for software developers: iOS, web design at bachelor's and master's level. Location (Connecticut) makes it difficult to attract talent.</td>
</tr>
<tr>
<td>Public Policy Company</td>
<td>201-500</td>
<td>No problem hiring bachelor's in economics/statistics/mathematics. Has found no shortages.</td>
</tr>
<tr>
<td>Research Institute A</td>
<td>1600</td>
<td>Easy to hire for: Mechanical, Aeronautical, Bioengineering. High demand for software engineering at all degree levels. Shortage of electrical engineers. Hiring for advanced degrees proved more challenging because of skillset mismatches</td>
</tr>
<tr>
<td>Research Institute B</td>
<td>1200</td>
<td>Works with DOD, does not hire internationals. Difficulty with hiring electrical and computer engineers (cannot compete with Silicon Valley companies for salary). A lot of applicants in public health disciplines. Much easier to hire in D.C. than in Kansas.</td>
</tr>
<tr>
<td>Venture Capital Com-</td>
<td>100</td>
<td>Difficult to find cross-disciplinary and well-rounded candidates with understanding of both business and technicals.</td>
</tr>
</tbody>
</table>
Bibliography

  URL: http://www.aip.org/sites/default/files/statistics/employment/phd1yrlater-p-10.pdf

  URL: http://www.psmag.com/science/the-real-science-gap-16191/

  URL: http://nypost.com/2011/06/24/americas-vanishing-science-jobs/

  URL: http://www.bls.gov/OES/current/oes151132.htm


Chapman, B. (2014). Top-performing high school seniors can get free ride to state colleges for science studies.
  URL: http://www.nydailynews.com/new-york/education/top-high-school-seniors-earn-free-state-tuition-science-studies-article-1.1782155

  URL: http://spectrum.ieee.org/transportation/systems/this-car-runs-on-code


de Lange, C. (2013). So you want to be a data scientist?
  URL: http://blogs.nature.com/naturejobs/2013/03/18/so-you-want-to-be-a-data-scientist


  URL: http://www.todaysengineer.org/2013/Dec/STEM-definition.asp
**URL:** http://ann.sagepub.com/content/327/1/132

Frenzel, L. (2013). Is there really a shortage of engineers?  
**URL:** http://electronicdesign.com/blog/there-really-shortage-engineers

Hampson, G. (2014). Guest: What do you mean by "STEM"?  
**URL:** http://seattletimes.com/html/opinion/2023128854_glennhampsonopedstem22xml.html?syndication=rss


**URL:** http://www.parl.gc.ca/content/hoc/Committee/411/HUMA/Reports/RP5937523/humarp09/humarp09-c.e.pdf


**URL:** http://www.census.gov/prod/2013pubs/acs-23.pdf

Larson, R. C. (n.d.). "STEM is for everyone".  
**URL:** http://www.wise-qatar.org/content/dr-larson-stem-everyone


**URL:** http://doi.wiley.com/10.1002/sres.2210

**URL:** https://www.wantedanalytics.com/analysis/posts/software-development-ranks-as-the-most-in-demand-skill-for-tech-jobs


URL: http://cen.acs.org/articles/90/123/Starting-Salaries.html

Munce, R. and Fraser, E. (2013). Where are the STEM Students? Where are the STEM Jobs?, Technical report, My College Options and STEMconnector, Summit, MO and Washington, DC.


URL: http://www.whitehouse.gov/sites/default/files/microsites/ostp/workforcdept.pdf


URL: http://www.nsf.gov/statistics/seind14/


Porretto, J. (2007). Oil companies scramble to find engineers.
URL: usatoday.com/money/industries/energy/2007-09-02-engineers_N.htm


The White House (2014). Educate to Innovate. URL: http://www.whitehouse.gov/issues/education/k-12/educate-innovate

Thibodeau, P. (2013). Electrical engineers see sharp uptick in Q1 jobless rate. URL: http://www.computerworld.com/s/article/923544/Electrical_engineers_see_sharp_uptick_in_Q1_jobless_rate

URL: http://www.jec.senate.gov/public/index.cfm?a=Files.Serve&File_id=6a9a7e1f-9586-47be-82e7-326f47658320

Vastag, B. (2012). U.S. pushes for more scientists, but the jobs aren't there.
URL: http://www.washingtonpost.com/national/health-science/us-pushes-for-more-scientists-but-the-jobs-arent-there/2012/07/07/gIQAZjpmUW_story.html

Wadhwa, V. (2011). Mr. President, there is no engineer shortage.
URL: http://www.washingtonpost.com/national/on-innovations/president-obama-there-is-no-engineer-shortage/2011/09/01/gIQAADpmpJ_story.html


Wright, J. (2013). America’s Skilled Trades Dilemma: Shortages Loom As Most-In-Demand Group Of Workers Ages.