Innovation and American K-12 Education

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Abstract: Economists have long believed that education is essential to the acquisition of human capital and driving economic growth. However, there is concern about the quality and costs of the K-12 education system in the United States and the implications for the development of the nation's future workforce. There have been calls for more innovation in K-12 education, leveraging technology in the classroom and experimenting with different organizing models for schools, both as a means to lower costs and increase quality. In this paper, I review the economics literature at the intersection between innovation and K-12 education from two different, but related, perspectives. First, I summarize the evidence about the efficacy of technological and other innovations in the classroom. Second, I discuss the state of research on how the American K-12 system influences the production of innovators and entrepreneurs. In both instances, I identify implications for policy and opportunities for future research to generate actionable insights.

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Introduction

A key objective of public policies designed to promote innovation is to develop, attract, and incentivize individuals who will generate new technological ideas. Much of the economics literature in this domain has focused either on increasing the “intensive” margin of innovation from the ranks of existing inventors via incentives and intellectual property policy (c.f. Stern 2004; Jaffe and Lerner 2011; Bell et al. 2016) or on contributing to the “extensive” margin via high-skilled immigrants, who have been found to contribute disproportionately to U.S. innovation and entrepreneurship (e.g., Saxenian 2007; Kerr and Lincoln 2010). However, economists have written far less about specific policies that can add to the extensive margin of innovation from a different source, namely developing the innovative and entrepreneurial potential of the native-born population.[1]

This gap is partially explained by the priorities of different sub-fields in the academic discipline of economics. While education economists have studied the American K-12 education system extensively, they have rarely assessed innovation-related metrics, focusing instead on broader outcomes such as test scores and graduation rates. For their part, innovation economists seldom study the K-12 education system directly, in favor of studying innovative outputs of firms, universities, and governments. As a result, there is still much to learn about how education policy can impact the domestic supply of innovators and whether new technological innovations can improve K-12 educational outcomes. Some recent academic work, discussed below, provides some intriguing insights for policymakers. However, the relatively small number of papers and

[1] There is existing work on innovation and entrepreneurship policies aimed at developing geographic regions, reviewed by Chatterji et al. (2014). Other scholars have focused on how higher education contributes to innovation and entrepreneurship (e.g., Stephan et al. 2004).

numerous remaining open questions underscore an emerging opportunity for economists interested in the intersection between innovation and education.

In this paper, I review two strands of literature that relate to the nexus between innovation and education. First, there is a small literature in economics that uses experiments to evaluate the impact of technology (hardware and software) on student achievement. I also briefly summarize the implications from work on how organizational innovations, such as new varieties of management practices, are related to student outcomes. Second, I discuss the emerging literature on how the design and curriculum of education systems relates to the production of an innovative workforce.

Technology, Productivity and Schools

There is a long tradition in the economics of innovation of estimating the productivity benefits from adopting new information technology (e.g., Stiroh 2002). While technology has enhanced productivity across various industrial sectors, it has arguably not had that effect in K-12 education, despite the great expectations of policymakers, the media and some technologists. Cutler (2011) reports that productivity growth in two key sectors, education and healthcare, grew quite slowly after 1995, in sharp contrast to the economy as a whole where numerous industries leveraged new technologies effectively.

There could be several reasons why education has not experienced rapid productivity gains via technology adoption. First, it is possible that the supply of high quality technologies is limited in comparison to other sectors due to low investment in research. R&D accounts for a tiny share of total expenditures in K-12 education, around 0.2%, or one-fiftieth of the rate of the most innovative industries (See Figure 1). This low level of investment is even more striking when one considers that total spending in K-12 spending is on the order of $600 billion a year, which is similar to expenditures in industries like pharmaceuticals (Chatterji and Jones 2012). What can explain this low level of R&D? It could be that the private value from commercializing innovations for use in K-12 schools is low. As discussed below however, this is not necessarily true. There is actually a very large market for education technology hardware and software in U.S., discussed further below. However, prior work by Chatterji and Jones (2012) has argued that the market structure of the sector makes it difficult for innovative entrants to thrive, stunting the development of new technologies.

Another, not mutually exclusive, possibility for the lack of IT-related productivity gains in American schools is that these organizations face endemic management challenges that hinder the adoption of promising technologies that could increase student achievement. Under this logic, productivity-enhancing technology is available, but organizations are not adopting it, whether from fears over substitution of labor for capital or disrupting existing curriculum. If this were a key factor, we would expect to observe different management practices and technology adoption rates across various kinds of schools, for example between private and public schools, which differ in terms of flexibility and incentives. We review some indirect evidence on this point below, though it is not clear that private schools more effectively use technological tools in comparison to public schools on average.

Understanding Technology Adoption in Schools

To develop a deeper understanding of what makes education technology distinct and resolve the puzzles posed above, we can leverage prior work in economics on technology adoption by firms. For both firms and schools, there is a classic information problem that arises when deciding whether to adopt a new technology. For many new technologies, it is difficult to demonstrate efficacy, particularly across heterogeneous customers, whether different kinds of firms or different kinds of schools. Without institutions to facilitate transparency about the efficacy of particular technologies, organizations that could benefit from a new technology still might not adopt it.

In other respects, the technology adoption decision for a school district is markedly different than that of a private sector firm. For example, it is not clear how a typical public school would necessarily capture the gains from adopting a technological tool that improved student outcomes. While firms can use new technologies to lower costs or improve product features for example, public schools do not seek profits and do not generally compete for students in the same way that firms compete for customers. Thus the incentives to adopt technology from a pure return on investment perspective are attenuated.

Another key challenge is related to the market structure of K-12 education. There are approximately 100,000 public schools and over 30,000 private schools in the U.S. [2], characterized by diverse preferences. One explanation is that the majority of decisions pertaining to schools are made at the local level and, with the exception of efforts such as the Common Core Standards, curricular choices can vary widely across the country. The result is, despite 100,000 potential customers, demand for education technologies in not sufficiently aggregated.[3] Designing technological tools in the absence of aggregated demand is challenging. For an innovator comparing the expected value (V) from successfully commercializing an innovation to the cost (C) of developing and selling it, this lack of aggregate demand implies that the costs, due

[2] The National Center for Education Statistics (https://nces.ed.gov/fastfacts/display.asp?id=84) Last accessed March 28th, 2017

[3] Large school districts, including the top five school districts which serve nearly 3 million students combined, do represent the potential for aggregated demand. See Chatterji and Jones (2012).

to implied customization for each idiosyncratic customer, are much higher than when customers are more homogenous. As C rises, assuming no increase in V, the incentives to develop innovation are weakened, limiting the number of high quality products available.

Another important feature of this setting, as discussed in Chatterji and Jones (2012), is that the instructional content market in education is dominated by three large textbook makers. Perhaps surprisingly, 70% of pre-K-12 instructional content is still printed material today[4]. These textbook companies leverage their large marketing and sales efforts to sell complementary education technology, in many cases tied to their textbooks. This market structure, coupled with the lack of institutions to independently assess efficacy, depress the expected value (V) for an innovator with a new technology. If the technology cannot be demonstrated to be effective, who will adopt it? And even if a handful of schools adopt the tool, how would the innovator scale these efforts to capture a larger part of the market? These uncertainties are one reason why rates of R&D spending and venture capital investment in education technology products might be comparatively low relative to the total size of the addressable market. As shown in Figure 2, investment is K-12 education technology ventures was $741 million in 2015 compared to nearly $60 billion across all industries in the same year.[5]

The discussion above suggests that the market structure in education and the complex process by which schools adopt and implement new technological tools can explain why this sector has not experienced dramatic productivity gains from IT. These themes will frame the

[4] “How are Digital Materials Used in Classrooms?” (http://www.edweek.org/ew/issues/technology-in-education/#distance)

[5] “$58.8 Billion in Venture Capital Invested Across U.S. in 2015, According to the MoneyTree Report” NVCA Press Release, January 15th, 2016. (http://nvca.org/pressreleases/58-8-billion-in-venture-capital-invested-across-u-s-in-2015-according-to-the-moneytree-report-2/)

next section of the paper, where I review specific studies of how innovation impacts student performance and other related outcomes.

The Impact of Technology on Student Performance

Federal policymakers have long emphasized the importance of providing computers and internet access in the classroom. For 15 year olds in the United States today, there is almost a 1-1 ratio between computers and students (Bulman and Fairlie 2016). The E-rate program, launched in 1998 and budgeted at $3.9 billion in 2015[6], provides schools and libraries with discounted internet access (Goolsbee and Guryan 2006). In part due to this program, nearly every classroom in the United States has Internet access (Fairlie et al. 2010) and 88% of school districts have high-speed broadband as of 2016, defined as 100 kbps per student.[7]

The market for education technology in the U.S. is estimated to be approximately $8 billion a year.[8][9] There has been a proliferation of technology emerging in American schools in recent years, with schools spending significant sums on hardware like tablets and laptops, interactive "smart boards", teacher training and digital curriculum[10]. There is also significant spending on enterprise software style solutions designing for managing student information and a large "after-school" market for mobile education applications. For one data point that reinforces

[6] Wyatt, Edward. "F.C.C. Increases Money for E-Rate Program for Internet in Schools and Libraries" The New York Times, December 11th, 2014. Last accessed February 26th, 2017
[7] EducationSuperHighway. "2016 State of the States" January 2017. (http://stateofthestates.educationsuperhighway.org/)
[8] Murphy, Meghan E. "As market surges, schools struggle to find the best tech products." The Hechinger Report, March 24th, 2015 (http://hechingerreport.org/as-market-surges-schools-struggle-to-find-the-best-tech-products/)
[9] Herold, Benjamin. "Technology in Education: An Overview" Education Week, February 5th, 2016 (http://www.edweek.org/ew/issues/technology-in-education/) Last accessed February 27th, 2017
[10] EdNET Insight, "State of the K-12 Market Report 2015" (http://schooldata.com/ednet-insight/)

the scale of this market, consider that there are currently 170,000 different education applications in Apple's App Store[11].

Proponents of greater use of technology in the classroom generally posit the following mechanisms by which student performance can be increased via the introduction of technology. First, as Barrow et al. (2009) argue, it is possible that technology can improve student performance by facilitating more hours of high-quality individualized instruction time. The authors discuss how access to computers and appropriate software can facilitate "personalized learning" whereby the education content is provided at a level appropriate for the student and consistent with their preferred mode of instruction. According to this logic, personalization could theoretically increase outcomes for high-performing and low-performing students. An ancillary, but possibly important benefit is that using technology in the classroom could also allow teachers to spend more time with each student, since a proportion of students could be occupied at any one time with computer aided instruction. This scenario poses technology as a substitute to teachers, as opposed to complement, a possibility that is discussed further below.

Aside from personalized instruction, digitized content that can be viewed across different hardware devices can broaden access to education, for example providing advanced placement courses to a geographically isolated school that does not have the appropriate staff or facilities. Via this channel, greater access via digitization of content could raise student achievement. Moreover, it could simply be that the user interface provided by digital tools enhances learning or that the mere presence of new technology in the classroom increases student motivation and engagement.

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[11] http://www.apple.com/education/products/ (Last accessed March 31st, 2017)

However, despite the ubiquity of technology in the classroom and various proposed mechanisms of action, rigorous evaluations of the impact of technology on student performance are rare and the results are mixed (Bulman and Fairlie 2016). Goolsbee and Guryan (2006) find that while E-Rate increased investments in education technology between 1996-2000 in California public schools, there was no statistical impact on student performance. This finding is consistent with other studies from the U.S. and around the world, which find little or no impact of technology on student outcomes (e.g., Angrist and Lavy 2002; Rouse and Krueger 2004). However, other studies have found some positive impact of technology on student performance, (Ragosta 1982; Banerjee et al. 2007; Machin et al. 2007; Barrow, Markman and Rouse 2009; Cheung and Slavin 2013; Muralidharan et al. 2016). As discussed in Barrow et al. (2009), these benefits must be considered in light of the costs of program adoption and ongoing implementation.

Several explanations have been offered for this apparent disconnect between the promise of technology and mixed empirical results. One rationale, supported by qualitative assessments, is that fidelity of implementation is the key barrier. While technology is present in the classroom, teachers and students may not use it (e.g., Cuban et al. 2001) or use it in sub-optimal ways (Wenglinsky 1998). For example, some recent high-profile technology interventions, such as a $1 billion tablet initiate in Los Angeles Unified School District, have been roundly criticized due to implementation challenges. In this instance, there were serious technical issues that prevented a large percentage of students from accessing the required curriculum.[12] Examples like these are consistent with the idea that several important complements must be in place to leverage

[12] Lapowsky, Issie. "What Schools Must Learn from LA's iPad Debacle", Wired. May 8th, 2015 (https://www.wired.com/2015/05/los-angeles-edtech/) Last accessed March 29th, 2017.

technological tools effectively, most notably high quality instructors and the appropriate curriculum.

It is important to note that if teachers and technological tools are complements instead of substitutes, the implications for productivity from a given intervention might be quite different. For example, to fully realize the benefits of a given technological tool that complements teachers, a school district may need to finance more training for their teachers or even hire additional staff, leading to increased costs, all else being equal. Contrast this scenario with one where teachers and technology, say tablets loaded with self-guided content, are viewed as substitutes. In this instance, substituting technology for labor might directly reduce costs.

Another explanation for the mixed results of technology interventions could be that some technological tools are quite conducive to learning but we do not know which ones. So the technologies that are most widely used are not those that are actually most beneficial for students. Currently, most education technologies do not undergo any kind of systematic and rigorous evaluation, which obscures efficacy and likely decreases incentives to innovate in the first place (Chatterji and Jones 2012). Without evidence of what works, schools adopt technological tools based on relationships with existing companies and the sales cycles are long and complex, dampening incentives for new entrants, as discussed above. As one illustration of this phenomenon, the famous venture capital firm Andreessen Horowitz reportedly refuses to invest in any education technology company where a school or district is intended to be the primary customer.[13]

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[13] "Catching on at last" The Economist, June 29th, 2013. (http://www.economist.com/news/briefing/21580136-new-technology-poised-disrupt-americas-schools-and-then-worlds-catching-last) Last accessed February 27th, 2017

Chatterji and Jones (2012, 2016) argue that low-cost and rapid evaluation methods could increase entry into the education technology sector, spur broader adoption of the most appropriate technologies and possibly raise student outcomes. One way to think about transparent and rapid evaluation is in the context of the innovator's decision discussed earlier. If a new technology could be quickly evaluated and compared to existing products, it would enhance the expected value, V, to prospective innovator. Moreover, it might also reduce costs, C, of marketing and selling the product to a diverse set of customers, since these buyers could presumably review the publicly available evaluation results directly. One further possibility is that existing demand aggregators, such as the League of Innovative Schools[14], might have preferences for adopting evidenced-based products. The increase in V and decline in C would increase the incentives for innovation and make venture investments in education technology companies more attractive, spurring future innovation and entrepreneurship. For a longer discussion on this point see Chatterji and Jones (2012).

There are other possibilities for the lack of consistent benefits from technology adoption in schools. For example, it is possible that technology is distracting students to a greater extent than it contributes to learning, which would be consistent not only with the empirical results from the academic literature but also numerous anecdotes from school administrators[15]. In addition, it could be that technologies are having a positive effect, but not on the skills that can be tested using traditional methods. For example, it could be that technology adoption by schools results in a higher level of technological fluency (e.g., greater comfort with various kinds of

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[14] The League of Innovative Schools (http://digitalpromise.org/initiative/league-of-innovative-schools/)
[15] Richtel, Matt, "In Classroom of Future, Stagnant Scores" The New York Times, September 3rd, 2011 (http://www.nytimes.com/2011/09/04/technology/technology-in-schools-faces-questions-on-value.html) Last accessed February 27th, 2017)

hardware and software) that might benefit students later in life, even if it does not directly impact test scores.

Another intriguing possibility is that specific kinds of education technology perform far better than others. In one of the most recent studies on this topic, Muralidharan, Singh and Ganimian (2016) find positive and economically large results for their computer-aided learning intervention in India, prompting them to categorize the literature in this domain as follows: Those interventions that have focused on supplying hardware alone have generally not been effective. Software programs that allow students to proceed through grade-appropriate material at their own speed produce small positive effects. The largest effects, present in their study and Banerjee (2007), emerge from software interventions that tailor the content to the student's ability, consistent with the personalized learning approach referred to above.

This suggestive pattern of results across studies highlights an important gap in the economics literature: Economists have done very little work to understand how students learn and how variations in these styles may impact human capital acquisition. While a large literature in education and psychology has explored how students learn, this work has not been connected in a meaningful way to economics.

Education technology that is "personalized" to the student can have several different connotations. First, a personalized software application to teach a particular skill could simply facilitate a different pace of instruction depending on the student. Some students could move faster and others could move more slowly, which may provide some advantages over traditional instruction, where adjusting the speed of delivery to each individual student would have practical limitations. Second, as discussed in Muralidharan et al. 2016, a software application could provide personalized content which adapts depending on the student's previous answers, providing the most appropriate level of instruction and focusing on key areas of weakness in a particular domain.

A third approach to personalization is software that is customized to each student's "learning style", defined by Pashler et al. (2008) as "the view that different people learn information in different ways". Pashler and co-authors argue that while learning styles is a popular concept in educational psychology and the popular press, there is little evidence to date that they actually exist. They argue that to demonstrate that individuals have different learning styles, not simply expressed preferences, a researcher would have to randomly assign different styles of instruction to different kinds of students and demonstrate that "correct" matches between students and styles actually leads to better performance. More research is required to document the existence and importance of learning styles and to explore the role specific education technology tools could play in matching students to the most appropriate content.

In terms of identifying promising technologies, there have been some recent efforts to spur increased research and development in the education technology space. In 2010, the President's Council of Advisors on Science and Technology (PCAST) proposed the creation of Advanced Research Projects Agency-Education (ARPA-Ed), modeled after the DARPA program to create technology platforms and digital curriculum, spurring innovation in the education sector (Lander and Gates 2010). A key challenge for these efforts is not simply the evaluations themselves but also the method by which the results are disseminated. While many kinds of hardware and content have diffused widely in schools, ranging from Khan Academy to smartboards, there is currently no system in place to incentivize the adoption of education technology that has been demonstrated to be effective. To address these concerns, Chatterji and Jones (2012, 2016) propose a platform to rapidly evaluate digital learning activities in the classroom using randomized controlled trials. Their platform, EDUSTAR, has evaluated 77 digital learning activities to date.

Organizational Innovations in K-12 Education

Recent work in economics and other fields emphasizes another important consideration for evaluating the promise of innovation in schools: how organizations are managed. Scholars who study private sector organizations have documented that the benefits of technology adoption depend heavily on the attributes of the organization. For example, Bloom et al. (2012) argues that recent U.S. productivity gains relative to Europe were driven by better “people management” practices among American firms in industries that intensively use IT, such as retail. Since there is significant variation across schools in terms of governance, human resource practices, size, strategy and culture, it could be that the adoption of technology is being hindered by existing management practices or organizational structures.

Bloom et al. (2015) find that the management of U.S. schools compares favorably to the other nations in their study, which is correlated with higher student outcomes. Further, charter schools have higher management scores than traditional public and private schools. This result is consistent with Angrist et al. (2013) and Dobbie and Fryer Jr (2013) who both find a positive relationship between specific management practices and school performance measures. Future research could explore the relationship between management practices at schools and the adoption and efficacy of new technologies. The findings could shed new light on how best to leverage new education technology to aid student learning. Moreover, the rise of new organizational models in education presents opportunities for research. While there is a large amount of research on charter schools (See Chabrier et al. (2016) for a recent summary) and school voucher programs (e.g., Ladd 2002), there is far less research on other kinds of schools with novel organizational structures and practices, such as STEM-focused schools and virtual schools (See Woodworth et al. (2015) for an exception).

K-12 Education and an Innovative Workforce

Next, I turn to the second major stream of work in this domain which explores the relationship between K-12 education and the creation of an innovative workforce. Economists have argued that U.S. productivity growth depends in large part on the knowledge-intensive sectors of the economy, which will increasingly require skilled workers to invent and use new technologies along with developing business models to commercialize them. This demand for skilled workers is thought to have been increasing in the 21st century, as firms shift from investing in production activities reliant on tangible capital to non-production activities more reliant on intangible capital. This change will require workers who have higher levels of skills in innovation, management, and marketing (Hulten and Ramey 2015). There is significant concern that the U.S. economy lacks the requisite number of skilled workers to capitalize on these trends (e.g., Augustine et al. 2010). Figure 3 illustrates that U.S. lags China and India in the number of STEM graduates per year, though many observers have pointed out the quality-based measures may be more informative indicators.

In response to these challenges, an emerging academic literature has focused on the allocation of talent in the U.S. economy and its implications for innovation. Much of this literature has focused at least in part on science, technology, engineering and mathematics (STEM) subjects, which are thought to be particularly important inputs to innovation (Augustine et al. 2010). At the university level, some work has found an association between STEM degrees and propensity to become an inventor (Aghion et al. 2015; Bianchi and Giorcelli 2017). Recent performance data suggests American secondary students are lagging behind peer nations in math and science achievement (Lander and Gates 2010; Hulten and Ramey 2015), a concern not only for innovation per se but perhaps also for these students' long-term employment outcomes (See Figure 4).

While specific policies to support STEM education in the United States can be traced back to at least the 1958 National Defense Education Act, which was designed to reform science curriculum in response to Soviet scientific achievements (Goodman 2017), it is only recently that a more targeted strategy has emerged. In 2010, the President's Council of Advisors on Science and Technology (PCAST) recommended the creation of a STEM Master Teacher Corps that could provide increased salary and compensation to STEM teachers and increase the number of STEM-focused schools to 1000 by 2020. The PCAST also called for the National Science Foundation and the Department of Education to develop a partnership and better coordinate the numerous disparate programs promoting STEM across the federal government (Lander and Gates 2010).

Fostering interest in STEM fields

Despite significant interest in expanding STEM education, there have been very few rigorous evaluations of the impact of these programs to date. There is some evidence that particular interventions can increase student interest in STEM fields. Hulleman and Harackiewicz (2009) employ a semester-long randomized controlled trial (RCT) with 262 high school science students and find that asking students to write monthly about the relevance of the course material to their own lives (compared to a control condition where the students summarize what they learn) increases student interest in science and their inclination to take science courses in the future.

There has also been interest in how exposure to the media, mentors and labor market signals influences students' selection into STEM fields of study and careers. Some scholars have explored how the "STEM pipeline" can break down, leading to students expressing interest in STEM early in their academic career but eventually pursuing other fields of study (e.g., Bettinger 2010). Shu (2016) examines a related conjecture that "the best and brightest" of U.S. college graduates are being drawn away from science and engineering based jobs to the financial industry by higher compensation. Using a sample of MIT graduates she does not find that lucrative opportunities in finance are drawing away talented would-be scientists and engineers. Shu concludes that finance and STEM jobs have different requirements and different kinds of preferred candidates and that it is below-average students who respond to shocks to finance salaries. While this study uses post-secondary education as an empirical context, it is possible that the perception of job opportunities may impact investments in STEM education in secondary school as well.

The impact of STEM on earnings

Next, there is some emerging evidence on the extent to which STEM education impacts earnings and the generation of new inventions later in life. Goodman (2017) finds evidence that an exogenous increase in math coursework during high school increased African-American student earnings by 3-4%. This study is especially notable because most of the prior literature in the economics of education focuses on the amount of *time in school*, as opposed to over which subjects that *time is allocated*. This point implicates a key concern in most studies aiming to establish a connection between STEM courses and long-term outcomes. High-ability students may select into STEM courses, confounding the relationship between these courses and outcomes like earnings, innovation or entrepreneurship. The most useful studies will be those that, like Goodman (2017), leverage exogenous variation in the amount of or quality of STEM coursework and measure long-term outcomes of students against a reasonable comparison group.

The basic logic behind increasing the absolute number of students studying STEM is that if more individuals acquire these skills, they will have better job prospects and drive economic growth via the increased introduction of new innovations. A recent paper by Bianchi (2016) however, identifies potentially important indirect effects at the university level that are important to consider. He studies the impact of a change in Italian law which allowed a large number of students to study STEM subjects in Italian universities for the first time during the 1960s. These new students came from technical high schools which generally offered a narrower and more applied menu of coursework than academic-track high schools. Academic-track high school students were always able to choose STEM majors in universities and the reform did not change this.

He finds that the introduction of these new students reduces academic performance of the incumbent academic track students, likely because of constraints on resources that increased faculty-to-student ratios and greater diversity in preparation across students. Further, Bianchi finds some high-potential students may have been induced to select non-STEM majors after the law was enacted. Finally, he finds some evidence that the law might have negatively impacted lifetime earnings for STEM graduates overall. These results suggest that policymakers considering expansions in STEM education opportunities should consider the possible direct and indirect impacts of such policies, what economists typically refer to as general equilibrium effects. These effects include not just the impact of a given policy on the absolute number of students who study STEM and their labor market outcomes, but also how these changes influence the economic returns to studying STEM (and other fields) for all students.

The link between STEM education and innovation

There is also new work that explores the link between STEM education and innovative activity later in life. Toivanen and Väänänen (2016) find that policy changes in Finland that led to greater opportunities to earn an engineering degree are related to the likelihood of patenting. Bianchi and Giorcelli (2017) investigate the relationship between STEM education and innovation using the same 1960s-era reform in Italian universities discussed above. The authors find that, after the law is enacted, high-achieving students (based on high school grades) are actually less likely to generate new inventions. However, students with lower high school achievement are more likely to generate new inventions, compared to similar students who matriculated before the law.

Interestingly the decrease in invention among high-achieving students was not necessarily from the highest potential prospective inventors. The authors use data on Italian inventors who patent in the U.S. (a proxy for quality) to conclude that the decline in patenting among individuals who were high-achieving students was likely concentrated among those who would not have produced the very best inventions. The authors note that these effects might be explained by the different occupational choices made by students after the change in law. This result indicates that broad expansions of STEM education may not only influence the number of inventions produced but also "who" produces them, via changing the composition of would-be inventors.

Another recent effort has taken a different approach to yield novel insights about the connection between STEM education and innovative activity later in the life. Bell et al. (2016) link federal tax returns and the U.S. patent data to investigate the link between human capital and innovation. They find that children of low-income parents (who are more likely to be in low-performing schools and have lower test scores) are far less likely to be inventors later in life, and that this disparity can be explained by differences that emerge in the early years of schooling. The authors also find that children who grow up in a region where innovation in a specific technology class is prevalent are more likely to invent in that technology class as adults. This result suggests that exposure to specific kinds of innovation in the early years might be important in how young people select their eventual fields of study and shape their decisions to become inventors. This logic could inform the design of many sorts of programs, for example mentoring initiatives for low-income children.

The authors conclude that, particularly as it relates to math education, reducing the relationship between parental income and achievement could contribute significantly to innovative output in terms of patents by unlocking the potential of more individuals to develop inventions. Card and Giuliano (2014) provide related evidence that the strategic use of gifted and talented programs could be one mechanism to achieve this objective. Their study of gifted and talented initiatives suggests that including disadvantaged students in these programs who do not meet the IQ cutoffs, but have scored well on state exams, may increase subsequent math and science performance for these students.

Skills beyond STEM and their role in innovation

It is important to note that not all scholars take for granted that America's relative standing on STEM education indicators, such as math and science test scores, is a valuable signal of our nation's future innovative and entrepreneurial capability. For example, Bhide (2008) argues that the large domestic market in the U.S. and the willingness of American consumers to experiment with new products is a central driver of innovation. Similarly, it is not clear the technical skills adequately measure the capacity for innovative entrepreneurship. Baumol (2005) observes that many successful entrepreneurs do not appear to have advanced technical training and only a small fraction have created breakthrough innovations on their own. Interestingly, Baumol notes a possible tension between the kind of foundational technical skills that underlie incremental innovation and the sort of novel and creative approaches required to develop radical innovations. He posits that America's lead in many innovation indicators is not due to the sheer number of technically trained citizens (an area where we lag behind some peer nations) but due in part the flexibility of our education system and its attitude towards creativity.

Relatedly, Levine and Rubinstein (2016) find that individuals who start incorporated businesses in the U.S. are more educated, score higher on exams, but also engage in more illicit activities, such as drug use, than their peers. These results are consistent with the idea that creative and less structured tasks such as innovation and entrepreneurship may favor individuals who deviate from accepted norms. This suggests that increasing STEM education at the expense of developing other skills could have an unintended impact on outcomes such as innovation and entrepreneurship.

Aside from math and science, other kinds of skills, including non-cognitive skills (Heckman 2006), could also be important in developing an innovative workforce. Cook et al. (2014) find large effects on math scores from an intervention in Chicago schools where they provided both academic and non-academic remediation for students who were at risk of dropping out of school. The academic component consisted of a daily, one-hour math tutoring session with 2 students per instructor. The non-academic component was cognitive behavioral therapy to improve problem-solving, impulse control and decision-making, delivered through 27 one hour weekly sessions. The authors find that participation in this program raised math test scores by the equivalent of 15 percentile points within the distribution of national scores and increased graduation rates by an estimated 14 percentage points.

Other, seemingly disparate, research in innovation and education suggest that teaching “soft skills” like social skills and teamwork in K-12 could play a role in increasing innovation and entrepreneurship. For example, consider Jones (2009), which documents the increase in teamwork in U.S. innovative activity, finding that inventor team size has increased by 35% from 1975-1999. More recently, Deming (2015) finds that between 1980 and 2012, jobs with high social skill requirements have increased by 10 percentage points as a share of the U.S. job market. If the results of these studies are considered in tandem, it implies that teamwork, which necessarily involves social skills to knit together larger groups of individuals, is crucial for developing new innovations. While individuals could learn teamwork in different settings, including at home, through military service and in employment, K-12 education could offer a particularly advantageous setting to develop these skills provided that we can develop evidence based practices.

Interestingly, it is notable that despite the significant attention from policymakers on STEM skills and to a lesser extent, non-cognitive skills, there is very little empirical work to my knowledge documenting the mechanisms by which increasing the skill level of a population can enhance the quality and quantity of innovation. While it seems plausible that more educated populations will produce more innovations, a relatively small share of citizens are directly involved in innovation in advanced economies. It is not clear whether raising the math and science skills of the average American student would have a significant impact on this metric, based on the current literature. Nor do we have any evidence that specific retraining programs lead to increases in the quality and quantity of innovation. These topics appear ripe for future research.

Conclusion: An Emerging Innovation Agenda for Education?

Despite a large amount of attention from policymakers and the media about the potential for technological innovation to yield dramatic improvements in our K-12 education system, we have yet to see significant gains in outcomes or reductions in cost. Relatedly, while it is commonly asserted that a skilled workforce, particularly in STEM subjects, will create more innovations, there is to date scant direct evidence for this conjecture either. These gaps present a tremendous opportunity to generate actionable policy insights.

Two broad themes emerge from this paper. First, prior work has argued that more rigorous and rapid evaluations of educational hardware and software can spur wider adoption of productivity enhancing technological tools in the classroom (Chatterji and Jones 2012). The proposed mechanism of action is that institutions that allow demonstration of “what works” will both provide stronger incentives to would-be innovators and facilitate broader scaling of useful technologies, particularly where demand is already aggregated. The emerging literature on this topic suggests that the kind of technology being tested is a first order concern (Muralidharan, Singh and Ganimian 2016). There is some initial evidence to suggest that “personalized” learning software is particularly promising in terms of raising student outcomes. But to properly deploy these tools, we first need a deeper understanding of how students learn. Moreover, an interesting complementary path will be to explore how organizational and pedagogical innovations facilitate student learning. Finally, there may be other kinds of outcomes, such as engagement or technological fluency, that could be assessed in these studies.

Second, there is clearly significant need for research that links educational interventions to longer-term outcomes, such as patenting and starting firms. The insights we do have in this domain (Bell et al. (2016) are dependent on access to sensitive government databases that can be costly and time consuming to acquire. To establish reliable evidence on which skills are connected to an innovative and entrepreneurial workforce, we will need more research utilizing these kind of data.

The workforce of tomorrow is in school today. Understanding how the hardware and content we provide to them shapes their acquisition of knowledge and long-term outcomes is a first-order economic policy issue. There remains a tremendous untapped opportunity at the intersection of innovation and education that has the potential to broaden access, increase quality and lower costs. Sustained research collaborations between government, academia and schools to generate actionable insights for policy appears to be a promising path forward.

References

Aghion, P., U. Akcigit, O. Toivanen and A. Vaananen (2015). "Living the American Dream in Finland: The Social Mobility of Innovators", unpublished manuscript.

Angrist, J. and V. Lavy (2002). "New evidence on classroom computers and pupil learning." The Economic Journal **112**(482): 735-765.

Angrist, J. D., P. A. Pathak and C. R. Walters (2013). "Explaining charter school effectiveness." American Economic Journal: Applied Economics **5**(4): 1-27.

Augustine, N. R., C. Barrett, G. Cassell, N. Grasmick, C. Holliday and S. Jackson (2010). "Rising above the gathering storm, revisited: Rapidly approaching category 5." Washington, DC: National Academy of Sciences, National Academy of Engineering, Institute of Medicine.

Banerjee, A. V., S. Cole, E. Duflo and L. Linden (2007). "Remedying education: Evidence from two randomized experiments in India." The Quarterly Journal of Economics **122**(3): 1235-1264.

Barrow, L., L. Markman and C. E. Rouse (2009). "Technology's edge: The educational benefits of computer-aided instruction." American Economic Journal: Economic Policy **1**(1): 52-74.

Baumol, W. J. (2005). "Education for innovation: Entrepreneurial breakthroughs versus corporate incremental improvements." Innovation Policy and the Economy **5**: 33-56.

Bell, A., R. Chetty, X. Jaravel, N. Petkova and J. Van Reenen (2016). "The lifecycle of inventors." unpublished manuscript.

Bettinger, E. (2010). To be or not to be: Major choices in budding scientists. American universities in a global market, University of Chicago Press**:** 69-98.

Bhide, A. (2008). The venturesome economy: How innovation sustains prosperity in a more connected world. . Princeton, N.J: Princeton University Press.

Bianchi, N. (2016). "The Indirect Effects of Educational Expansions: Evidence from a Large Enrollment Increase in STEM Majors". unpublished Manuscript.

Bianchi, N. and M. Giorcelli (2017). "Scientific Education and Innovation: From Technical Diplomas to University STEM Degrees". unpublished manuscript.

Bloom, N., R. Lemos, R. Sadun and J. Van Reenen (2015). "Does management matter in schools?" The Economic Journal **125**(584): 647-674.

Bloom, N., R. Sadun and J. Van Reenen (2012). "Americans do IT better: US multinationals and the productivity miracle." The American Economic Review **102**(1): 167-201.

Bulman, G. and R. W. Fairlie (2016). "Technology and education: Computers, software, and the internet", NBER Working Paper No. 22237.

Card, D. and L. Giuliano (2014). "Does gifted education work? For which students?", NBER Working Paper No. 20453.

Chabrier, J., S. Cohodes and P. Oreopoulos (2016). "What Can We Learn from Charter School Lotteries?" The Journal of Economic Perspectives **30**(3): 57-84.

Chatterji, A. and B. Jones (2012). "Harnessing Technology to Improve K-12 Education. ." The Hamilton Project, Discussion Paper 2012-05.

Chatterji, A. and B. Jones (2016). "Learning What Works in Educational Technology with a Case Study of EDUSTAR." The Hamilton Project, Policy Memo 2016-01.

Cheung, A. C. and R. E. Slavin (2013). "The effectiveness of educational technology applications for enhancing mathematics achievement in K-12 classrooms: A meta-analysis." Educational research review **9**: 88-113.

Cook, P. J., K. Dodge, G. Farkas, R. G. Fryer Jr, J. Guryan, J. Ludwig, S. Mayer, H. Pollack and L. Steinberg (2014). "The (surprising) efficacy of academic and behavioral intervention with disadvantaged youth: results from a randomized experiment in Chicago", NBER Working Paper No. 19862.

Cuban, L., H. Kirkpatrick and C. Peck (2001). "High access and low use of technologies in high school classrooms: Explaining an apparent paradox." American Educational Research Journal **38**(4): 813-834.

Cutler, D. M. (2011). "Where are the health care entrepreneurs? The failure of organizational innovation in health care." Innovation Policy and the Economy **11**(1): 1-28.

Deming, D. J. (2015). "The growing importance of social skills in the labor market.", NBER Working Paper No. 21473.

Dobbie, W. and R. G. Fryer Jr (2013). "Getting beneath the veil of effective schools: Evidence from New York City." American Economic Journal: Applied Economics **5**(4): 28-60.

Fairlie, R. W., D. O. Beltran and K. K. Das (2010). "Home computers and educational outcomes: evidence from the NLSY97 and CPS." Economic Inquiry **48**(3): 771-792.

Goodman, J. (2017). "The Labor of Division: Returns to Compulsory High School Math Coursework", NBER Working Paper No. 23063.

Goolsbee, A. and J. Guryan (2006). "The impact of Internet subsidies in public schools." The Review of Economics and Statistics **88**(2): 336-347.

Heckman, J. J. (2006). "Skill formation and the economics of investing in disadvantaged children." Science **312**(5782): 1900-1902.

Hulleman, C. S. and J. M. Harackiewicz (2009). "Promoting interest and performance in high school science classes." Science **326**(5958): 1410-1412.

Hulten, C. and V. Ramey (2015). "Introduction: Skills, Education, and US Economic Growth: Are US Workers Being Adequately Prepared for the 21st Century World of Work?". Education, Skills, and Technical Change: Implications for Future US GDP Growth, University of Chicago Press.

Jaffe, A. B. and J. Lerner (2011). Innovation and its discontents: How our broken patent system is endangering innovation and progress, and what to do about it, Princeton University Press.

Jones, B. F. (2009). "The burden of knowledge and the "death of the renaissance man": Is innovation getting harder?" The Review of Economic Studies **76**(1): 283-317.

Kerr, W. R. and W. F. Lincoln (2010). "The supply side of innovation: H-1B visa reforms and US ethnic invention." Journal of Labor Economics **28**(3): 473-508.

Ladd, H. F. (2002). "School vouchers: A critical view." The Journal of Economic Perspectives **16**(4): 3-24.

Lander, E. S. and S. J. Gates (2010). "Prepare and inspire." Science **330**(6001): 151-151.

Levine, R. and Y. Rubinstein (2016). "Smart and Illicit: Who Becomes an Entrepreneur and Do they earn more?" The Quarterly Journal of Economics: qjw044.

Machin, S., S. McNally and O. Silva (2007). "New technology in schools: Is there a payoff?" The Economic Journal **117**(522): 1145-1167.

Muralidharan, K., A. Singh and A. J. Ganimian (2016). Disrupting Education? Experimental Evidence on Technology-Aided Instruction in India, NBER Working Paper No. 22923.

Pashler, H., M. McDaniel, D. Rohrer and R. Bjork (2008). "Learning styles concepts and evidence." Psychological Science in the Public Interest **9**(3): 105-119.

Ragosta, M. (1982). Computer-assisted Instruction and Compensatory Education: The ETSI LAUSD Study Washington, DC, National Institute of Education.

Rouse, C. E. and A. B. Krueger (2004). "Putting computerized instruction to the test: a randomized evaluation of a "scientifically based" reading program." Economics of Education Review **23**(4): 323-338.

Saxenian, A. (2007). The new argonauts: Regional advantage in a global economy. Cambridge,MA, Harvard University Press.

Shu, P. (2016). Innovating in Science and Engineering or'Cashing In'on Wall Street? Evidence on Elite STEM Talent. unpublished manuscript.

Stephan, P. E., A. J. Sumell, G. C. Black and J. D. Adams (2004). "Doctoral education and economic development: The flow of new Ph. Ds to industry." Economic Development Quarterly **18**(2): 151-167.

Stern, S. (2004). "Do scientists pay to be scientists?" Management science **50**(6): 835-853.

Stiroh, K. J. (2002). "Information technology and the US productivity revival: A review of the evidence." Business Economics **37**(1): 30.

Toivanen, O. and L. Väänänen (2016). "Education and invention." Review of Economics and Statistics **98**(2): 382-396.

Wenglinsky, H. (1998). "Does it compute? The relationship between educational technology and student achievement in mathematics". Princeton, NJ, Educational Testing Service.

Woodworth, J. L., M. Raymond, K. Chirbas, M. Gonzalez, Y. Negassi, W. Snow and C. Van Donge (2015). "Online Charter School Study 2015". Stanford, CA: Center for Research on Education Outcomes, Stanford University.

Figure 1: R&D Spending by Industry

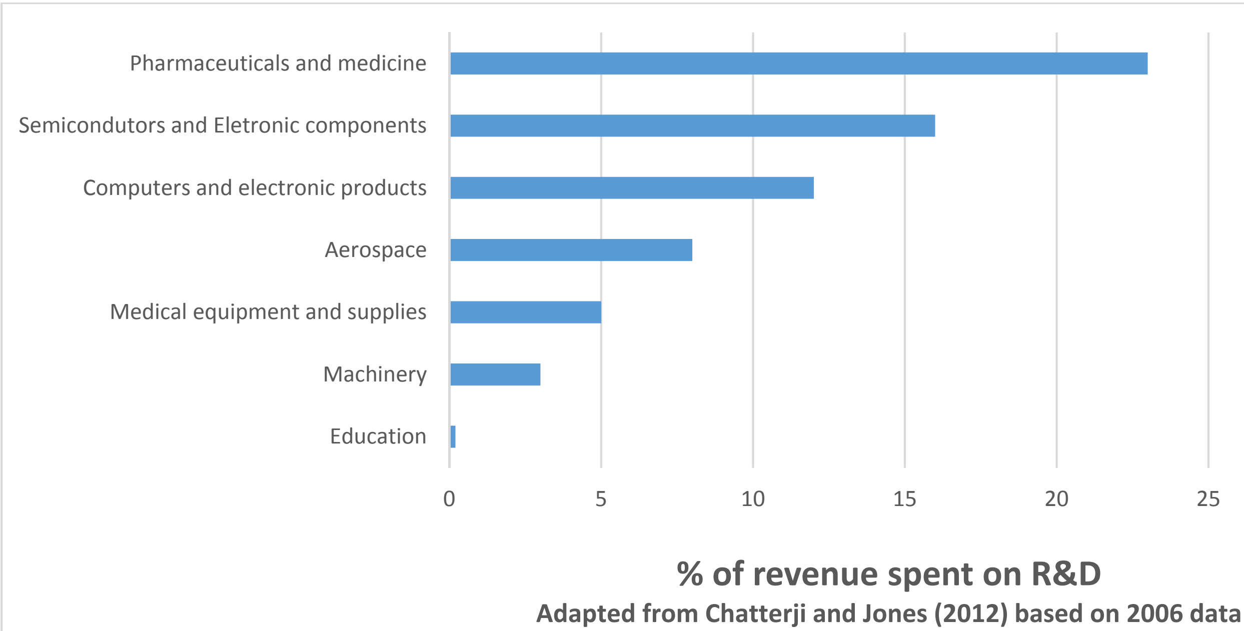
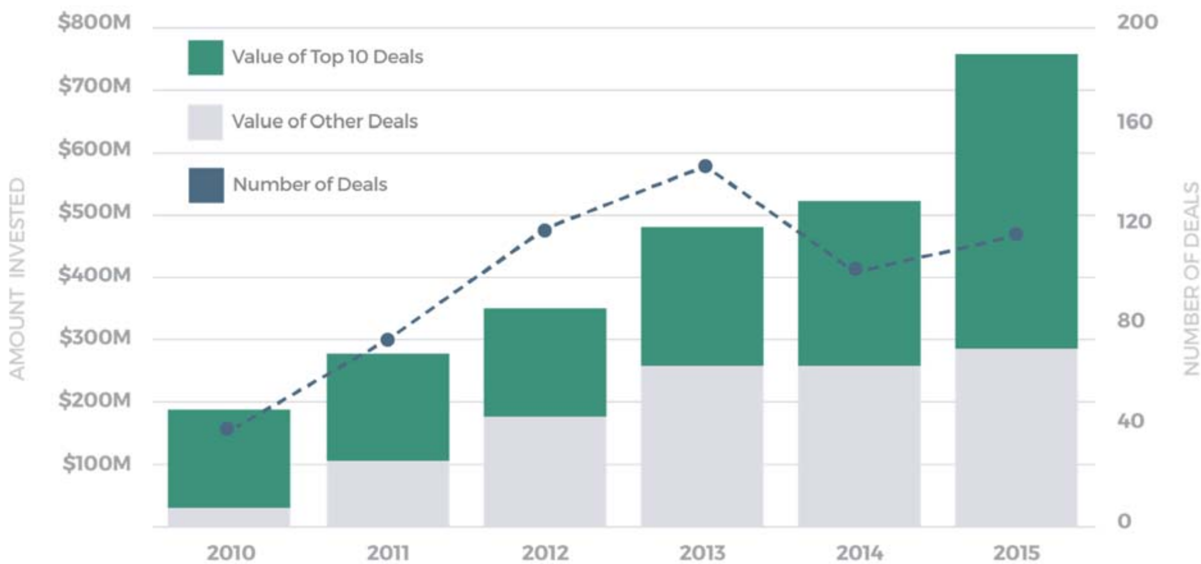
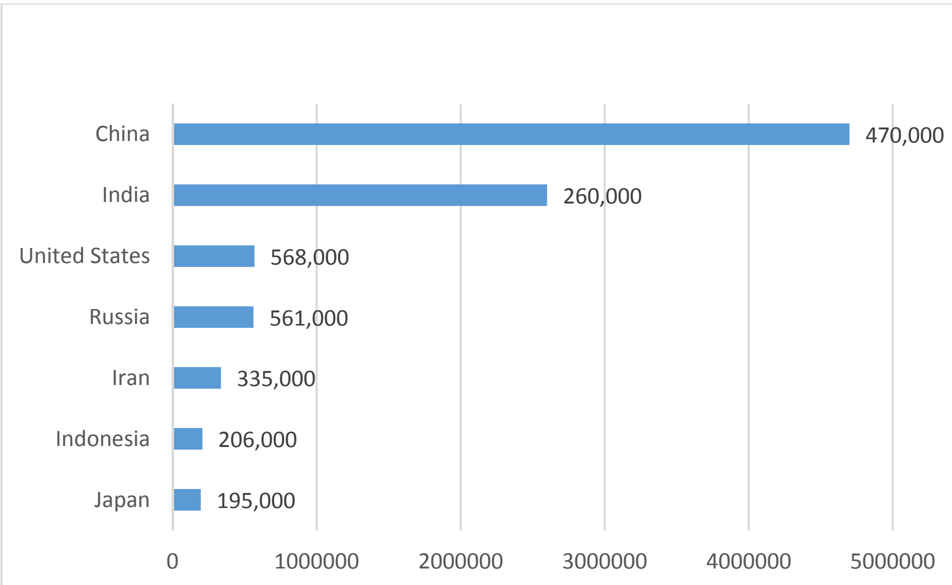


Figure 2: Investments in Education Technology Companies (2010-2015)



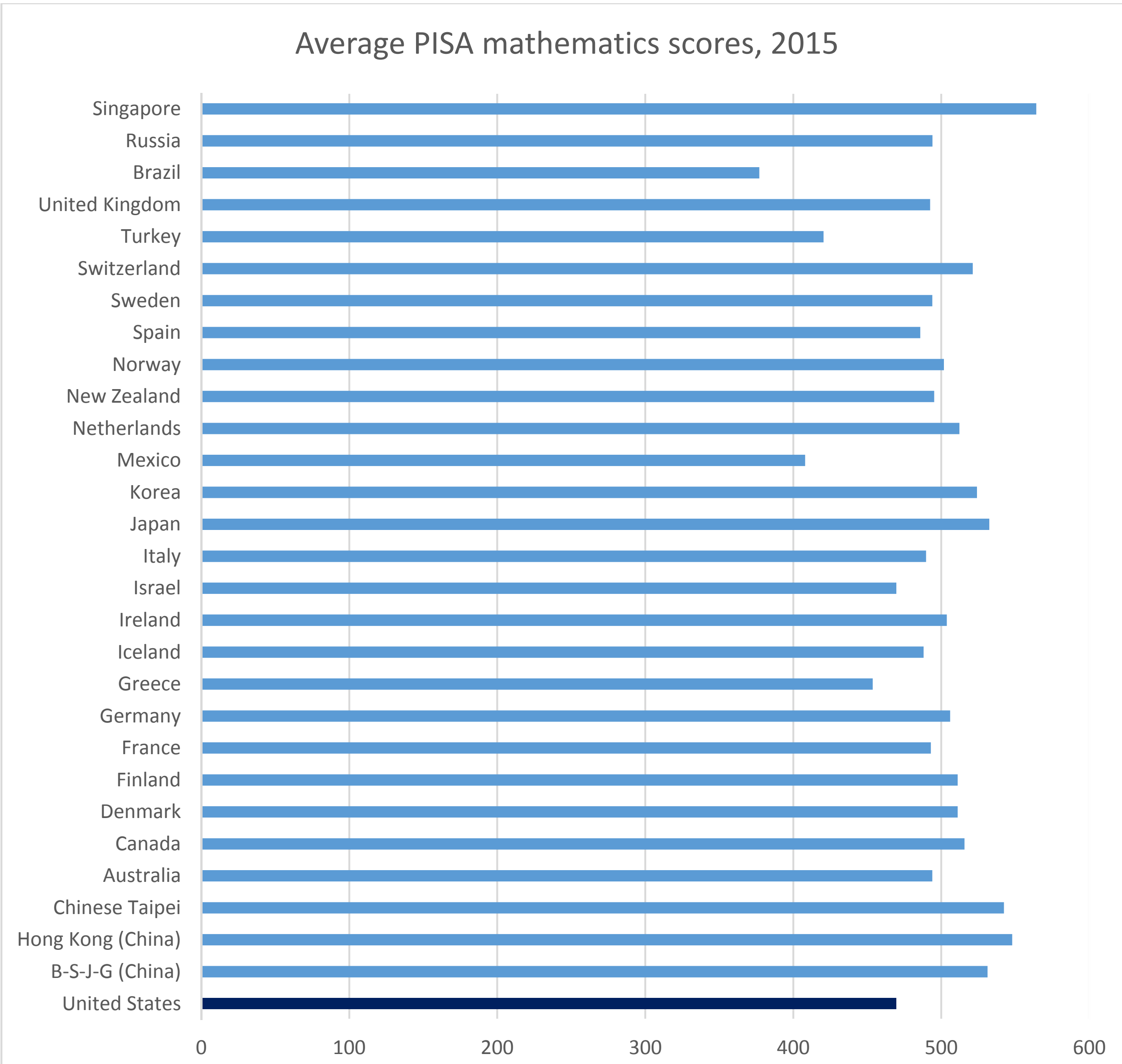
Source: EdSurge (https://www.edsurge.com/research/special-reports/state-of-edtech-2016/funding#investments)

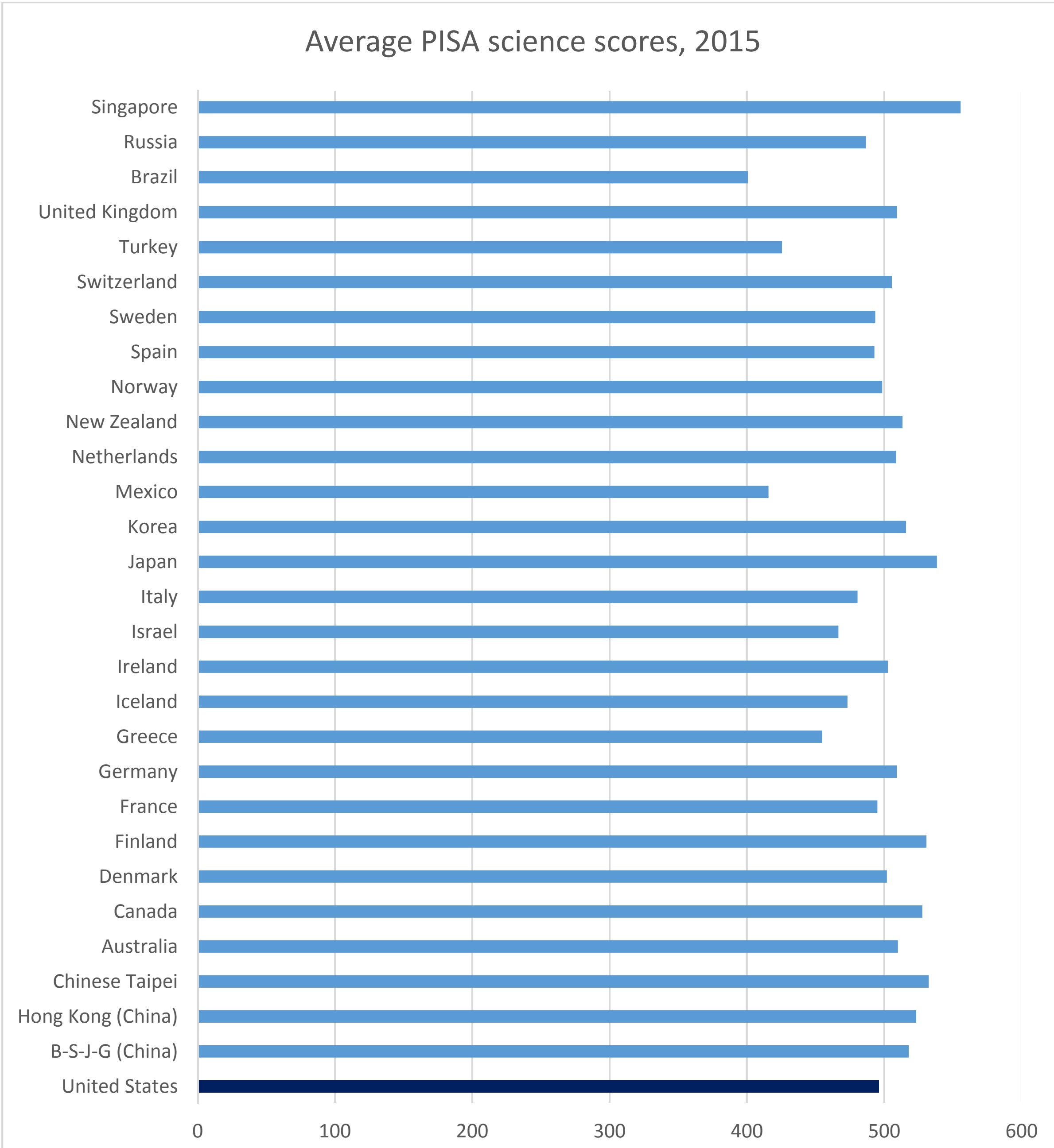
Figure 3: STEM Graduates by Selected Countries, 2016



Source: World Economic Forum Data

Figure 4: International Math and Science Scores for High School Students





Average PISA science scores, 2015
Singapore
Russia
Brazil
United Kingdom
Turkey
Switzerland
Sweden
Spain
Norway
New Zealand
Netherlands
Mexico
Korea
Japan
Italy
Israel
Ireland
Iceland
Greece
Germany
France
Finland
Denmark
Canada
Australia
Chinese Taipei
Hong Kong (China)
B-S-J-G (China)
United States
0
100
200
300
400
500
600