How High-Skill Immigration Affects Science: Evidence from the Collapse of the USSR

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Abstract: A commonly cited reason for increasing high-skill immigration to the United States is the perceived positive impact that such immigrants would have on the course of U.S. science. While it is true that scientific research is particularly important for long-term economic wellbeing, and while it is also true that immigrants have historically accounted for a disproportionate share of U.S. scientific output, the causal impact of an increase in the number of high-skill immigrants on U.S. science is not obvious. An influx of new knowledge and knowledge-generating workers may generate knowledge spillovers: the productivity-enhancing peer effects that must be present if high-skill immigration is to have beneficial long-run effects. However, scientists must also compete for scarce resources such as jobs, journal space, and attention, in order for their research to be produced, disseminated, and used. This paper reviews the evidence we report in recent work (Borjas and Doran, 2012, 2014) that simultaneously addresses both of these conflicting forces. The research uses the "natural experiment" created by the collapse of the Soviet Union, which led to the largest sudden influx of scientific personnel and ideas into the United States since World War II. In this context, there is little evidence of improved productivity among pre-existing scientists after a sizable supply and idea shock.

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I. Introduction

Many politicians, economists, and policy experts view high-skill immigration as an engine of economic growth, innovation, and well-being. This widespread perception is reinforced by the history of great immigrant scientist/inventors, such as Alexander Graham Bell and Enrico Fermi, and by statistics showing that immigrants are over-represented in scientific achievement. Certainly, many of the products and technologies that drive economic growth today were made possible by fundamental scientific advances of the past century, in which foreign-born scientists often played a key role. So it is not surprising that this history informs the underlying assumptions behind recent calls for attracting more immigrant scientists.

Descriptive statistics and anecdotal evidence, however, are inadequate guides for predicting the causal effects of increased high-skill immigration. In this paper, we summarize the evidence that is revealed once we move beyond the descriptive statistics and focus instead on carefully measuring causal impacts resulting from the largest scientific influx that the United States has experienced since World War II—specifically, the migration of many world-class Soviet mathematicians into the U.S. workforce after the collapse of the Soviet Union.

An increase in immigration unleashes multiple economic forces, and the net effect on economic wellbeing can be difficult to predict in advance. On the one hand, it is well

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known that the gains from immigration to a receiving country may be substantial when the immigrant influx is composed mainly of high-skill workers *and* when the interaction between the high-skill immigrants and the pre-existing native workforce generates positive productivity spillovers. In the absence of such spillovers, the net gains from high-skill immigration could only arise from the presence of capital-skill complementarities, and these gains would become attenuated over time as the capital stock adjusts in response to the immigrant influx. Many economists believe that human capital spillovers are likely to be strong, so that long-run improvements in productivity and economic wellbeing are a real possibility.[1]

On the other hand, this optimistic perception needs to be tempered by concurrent economic forces. The scientific interactions that generate positive spillovers happen in a "real world" where scientists may not be able to produce science unless they are employed by an organization that supports them in that goal, and may not be able to disseminate their research findings unless there are journals to publish them and readers to read them. The influx of high-skill immigrants not only generates a supply shock in the space of ideas (e.g., new knowledge that may make native workers more productive), but also increases the number of high-skill workers participating and competing for jobs in the scientific labor market and competing for space in the scientific journal market. If resources in these markets are relatively constrained (e.g., a limit in the number of faculty slots or in the amount of resources available for research grants), large and sudden increases in the

[1] This conclusion, of course, is related to the widely held belief that the source of long-term economic growth lies in human capital. The foundation of modern models of economic growth, in fact, is the assumption that there are strong human capital externalities (Lucas, 1988; Romer, 1986, 1990), and that these externalities create the potential for continuous long-term growth.

population of scientists can crowd out some of the pre-existing workers and reduce their productivity.

This paper summarizes the evidence from our investigation of a recent natural experiment that led to a substantial increase in the stock of ideas *and* in the number of high-skill workers in a narrowly defined scientific field: the impact of the influx of renowned Soviet mathematicians into the American mathematics community after the collapse of the Soviet Union. In any study of the causal effects of high-skill immigration, it is essential to distinguish what did occur from what would have occurred in the absence of immigration. Not only did the exodus of Soviet mathematicians after the collapse of the Soviet Union lead to a very large influx of new scientific talent into the United States, but it also turns out that unique details of this influx make it possible to distinguish what actually happened from what would have happened in the absence of this immigration.

In particular, in the period between the establishment and the fall of communism, Soviet mathematics developed in an insular fashion and along very different specializations than American mathematics. As a result, some U.S. subfields experienced no potential insights from Soviet mathematics after the collapse of the Soviet Union, while other fields experienced a flood of new mathematicians, theorems, and ideas. We can therefore compare outcomes of mathematicians who worked on topics the Soviets could help them with (*and* compete with them on) with the outcomes of mathematicians who worked on topics the Soviets knew little about. This comparison establishes a useful benchmark for what would have occurred had there been no influx of Soviet mathematicians.

The evidence unambiguously indicates that almost all American mathematicians whose research agenda overlapped with that of the Soviets experienced a reduction in the number of papers written and the number of citations received after the entry of the Soviet émigrés. In short, the adverse competitive effects resulting from an increase in the number of workers outweighed the beneficial spillover effects resulting from an increase in the stock of ideas. The evidence also indicates that the adverse productivity effect worked through a number of channels: American mathematicians whose research overlapped with that of the Soviets became much more likely to switch institutions; the job switch entailed a move to a lower quality institution; and many of the affected American mathematicians ceased publishing relatively early in their career.

Moreover, the conclusion that the net productivity effect was negative is independently confirmed by observing the reaction of American mathematicians "on the ground" to the supply shock. When a supply shock raises or lowers the productivity of native workers, the changed economic opportunities will induce behavioral reactions in response. In fact, knowledge producers can respond to supply shocks by moving their efforts either to research topics that have now become more profitable or away from research topics where the additional competition makes it harder to succeed. The *direction* of flows of "cognitive movers" thus provides independent information about the relative importance of human capital spillovers in the knowledge production sector. As people "vote with their minds," they reveal private information about relative productivities in different locations of idea space that counts of publications, patents, and citations may miss.

It turns out that many American mathematicians moved *away* from the research topics favored by the Soviets—the topics that were presumably infused with many new theorems and techniques. Moreover, newly minted American mathematicians also chose to stay away from Soviet-style topics when preparing their dissertations. In short, the reaction of the mathematicians most affected by the supply shock clearly suggests that the adverse productivity effects associated with a larger workforce dominated.

The aggregate impact of these repercussions of the Soviet supply shock was mainly distributional. There was no increase in the total "output" of the mathematics community in the United States, at least as measured by the number of papers or citations. The American mathematicians whose research interests most overlapped with those of the Soviets produced far less research output after 1992, but this loss was compensated by the output of the Soviets themselves. Put differently, the supply shock did not change the size of the "mathematics pie" in the United States.

The evidence implied by this particular natural experiment is not consistent with the optimistic view stressed by Jones and Romer (2010) that the ideas of one highly skilled worker will necessarily induce greater idea generation by other highly skilled workers. In contrast, we find that the average worker in the pre-existing workforce becomes less productive when new ideas *and* workers are exogenously introduced into the mix. Our evidence thus suggests that it is far from inevitable that the spillovers emphasized by the economic growth literature will "win" the race between human capital externalities and the scarcity of resources. Put bluntly, an increase in immigration of high-skill workers may not necessarily generate substantial long-run gains for the native population.

In Section II, we discuss the historical background of the influx of Soviet mathematicians, emphasizing the unique features of this shock that allow us to determine what would have occurred in the absence of the Soviet influx. In Section III, we document the difference in the productivity trends of American mathematicians who were exposed to new people and ideas and American mathematicians who were not. Section IV decomposes the overall productivity effects of the immigration shock into its components, including citations, the probability of writing "important" papers, the extent of coauthorships, job turnover, and the probability of retiring. In Section V, we argue that the research choices of mathematicians reveal their private information about how the shock affected their productivity across fields and document that American mathematicians persistently stayed away from “Soviet-style” research topics after the supply shock. Section VI summarizes the aggregate impact of the shock on the total output of the American mathematics community. Finally, Section VII discusses potential policy implications.

II. History

Since the founding of the USSR in 1922, Soviet policies caused Soviet and Western mathematics to develop along independent trajectories. What is now known as the "Luzin affair" provides an illustrative example of Soviet policy. In 1936, Nicolai Luzin, a mathematician at Moscow State University and a member of the USSR Academy of Sciences, became the target of a Stalinist political prosecution. In addition to the catch-all charge of "promoting anti-Soviet propaganda," Luzin was also accused of reserving his most significant mathematical results for foreign publication. Though Luzin escaped execution, the Soviet scientific community took the incident as a warning, and began to publish almost exclusively in the Russian language and in Soviet journals.

Soviet scientists were subject to many draconian regulations regarding communication with Western colleagues, academic travel, acceptable publication outlets, and access to Western resources. Consider the following description of the intellectual climate in the USSR by a historian of Soviet mathematics (Polyak, 2002):

> When Professor Ya.Z. Tsypkin received a letter in the late 1940s from an American reader of his paper, he was summoned by the KGB and underwent a long investigation there, tottering at the edge of arrest. . . Another source of difficulties for researchers was the mania for secrecy. . . All letters abroad (as well as letters from abroad) were opened and inspected. Everybody must have special permission, and a full text of the talk had to be approved if you were going to an international conference. And working in a classified institution (which was the case for many experts in mathematical programming), complicated the situation drastically.

Not surprisingly, with so little contact, 20th century mathematics developed differently in the Soviet Union and the West. It is well known that two peoples, who once shared a common language, will quickly develop different dialects if all contact between them ceases. In the same manner, Western and Soviet mathematicians developed their own unique specializations on each side of the Iron Curtain. Figure 1 illustrates the significant differences in research focus. In the USSR, the most popular fields prior to the collapse of communism included partial and ordinary differential equations. Indeed, almost 20% of papers published in the Soviet Union were in these two fields alone. Conversely, American mathematicians only published 5% of their papers in these fields, but devoted 15% of their published output to statistics and operations research--both of which were relatively unpopular topics in the USSR.

Though the collapse of communism may in hindsight seem to have been inevitable, it took even seasoned experts by surprise. As one historian describes it, in the Soviet Union, “most believed the system was so strong that it would never essentially change. Others, more optimistic, thought that change was perhaps possible over a long period – decades, or more likely, generations” (Laqueur, 1996, p. 65). Western Sovietologists knew no better: "the U.S. government (like most others) had enormously overrated Soviet economic performance and . . . the statisticians, in the intelligence community as in academe, were in a state of disarray. According to a study published as late as 1988 by a well-known Western economist specializing in the Soviet Union, Soviet citizens enjoyed 'massive economic security' . . . the consensus was that the Soviet Union was *not* on the verge of economic bankruptcy and political disintegration" (Laqueur, 1996, p. 99).

Beginning around 1990, the chaotic political situation in the Soviet Union allowed Soviet scientists a new-found freedom. They began the first sustained intellectual contact with the West in decades and visited the West frequently, often with the goal of permanently relocating. Some American scientists, meeting their long-estranged colleagues for the first time, found the contact exhilarating. As the *New York Times* reported in 1990 (Kolata, 1990):

> "American scientists say they have benefited immensely from the [recent] Soviet visitors. . . Persi Diaconis, a mathematician at Harvard, said: 'It's been fantastic. You just have a totally fresh set of insights and results.' Dr. Diaconis said he recently asked [Soviet mathematician] Dr. Reshetikhin for help with a problem that had stumped him for 20 years. 'I had asked everyone in America who had any chance of knowing' how to solve a problem . . . No one could help. But . . . Soviet scientists had done a lot of work on such problems. 'It was a whole new world I had access to,' Dr. Diaconis said. 'Together, we'll be able to solve the problem.'"

But in addition to the obvious positive knowledge spillovers, the American mathematical community experienced increased competition in hiring. Another *New York Times* article (Howe, 1990) noted this increased competition:

> Even more Soviet scholars want to come. American scientists say they are being peppered with letters and calls asking for invitations. 'It seems like I get a letter from the Soviet Union every two or three days,' said Dr. Ablowitz of the University of Colorado... Soviet scientists are traveling throughout the United States. 'I have run across a number of very distinguished Soviet mathematicians who have come here as visitors and spend their time going around the country and looking for a job,' Dr. Nathanson said.

Not surprisingly, when the unemployment rate for new mathematics doctorates hit a high of 12 percent in 1991, the American Mathematical Society's 1991-1992 Academic Hiring Survey laid the blame on "increased numbers of highly qualified recent U.S. immigrants seeking employment in academia" (McClure, 1992).[2] Figure 2 illustrates these employment trends. Clearly, at the time of the Soviets' arrival, there was both a significant increase in the unemployment rate for new Ph.D. holders in mathematics, as well as a significant decrease in the likelihood of receiving employment at a research university.

The influx of Soviet mathematicians to the United States circa 1991 thus shows two competing economic forces at work. On the one hand, the removal of communication and travel barriers drastically lowered the costs of collaboration. Both Soviet and Western mathematicians gained access to a huge new supply of knowledge, skills, and expertise from the opposite group. In particular, the different field specializations of Soviets and Westerners meant that each side received a supply shock of previously undiscovered knowledge, with the potential for large positive spillovers in productivity. On the other hand, the knowledge shock was accompanied by a "traditional" labor supply shock, namely an increase in the number of workers. Many high-skill Soviet mathematicians sought employment in the U.S., making it more difficult for mathematicians already residing in the United States to find work.

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[2] The exodus of key scientific personnel from the former Soviet Union to the West was one of the key reasons that led George Soros to establish a program that provided research funds to those scientists who chose to remain; see Ganguli (2010) for an analysis of the impact of this program on career choices.

III. Productivity Trends for American Mathematicians

The American Mathematical Society (AMS) maintains a database that contains complete information on the publication and citation record of all mathematicians since 1939. Each publication entry lists all authors, the institutions they are affiliated with, which field of mathematics (out of 73) the paper is focused on, and the total number of citations the paper has ever received.

With this information, it is possible to create groups of American mathematicians, Soviet mathematicians, and Soviet émigrés.[3] The subsample of Soviet émigrés had exceptionally high productivity both before and after the migration. Prior to their move, the future émigrés were significantly more productive in terms of the number of papers published and citations received. In particular, before 1992 the average (future) émigré had published 10 more papers and received 45 more citations than the typical Soviet mathematician who did not migrate to the United States. After 1992, the émigrés' productivity far surpassed that of the pre-existing American mathematicians. Between 1992 and 2008, the average Soviet émigré published 19 more papers than the average American, and those papers received 144 more citations. In short, the Soviet émigrés originated in the upper tail of the skill distribution of mathematicians in the Soviet Union and quickly moved into the upper tail of the skill distribution in the American mathematics community. The positive selection of the émigré sample, therefore, raises a strong

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[3] We define an American (Soviet) mathematician as anyone affiliated with an American (Soviet) institution for at least half of his papers published before 1990. A Soviet mathematicians is then defined as an émigré if more than half of his post-1990 papers lists an American affiliation. These definitions imply a pre-existing population of 29,392 predominantly American mathematicians and 12,224 Soviet mathematicians. We also find that 1,051 of these Soviet mathematicians emigrated after the collapse of the Soviet Union, with 336 of the émigrés moving to the United States.

possibility that they would generate beneficial productivity spillovers after their move to the United States.

Given the pre-1992 disparity between American and Soviet research interests, it is not surprising that the "supply shock" affected some mathematical fields much more than other mathematical fields. Figure 3 illustrates the magnitude of the supply shock on two different types of fields: Soviet-style and American-style fields. The figure shows that the supply shock, as defined by the fraction of total papers published by Soviet émigrés, was very large for the fields prevalent in the Soviet Union, and very small for the fields that traditionally attracted American mathematicians. The fraction of papers published in the United States by Soviet émigrés in "Soviet-style" fields rose from a negligible fraction before 1992 to about 12 percent. In contrast, the fraction of papers published by the Soviet émigrés in "American-style" fields was below 4.0 percent throughout the post-1992 period. In short, not all American mathematicians were equally affected by the Soviet influx, and it is this differential shock that provides the method for determining the productivity impact of the collapse of the Soviet Union on American mathematics.

Consider, for instance, the changed opportunities faced by an American mathematician specializing in statistics. There would have been relatively little direct job competition since mathematicians who specialize in statistics will not, in general, be competing for the same positions as mathematicians who specialize in differential equations. Moreover, because of the intellectual differences among mathematical fields, it is unusual for a paper published in statistics to cite results from papers published in differential equations. Hence the possibility of cross-fertilization in ideas is also small. The typical American statistician, therefore, probably was little affected by the Soviet influx.

In contrast, some Americans were specializing in Soviet-style topics prior to 1992. It is this subset of Americans who could both gain *and* lose as a result of the Soviet influx. They would be competing for the same jobs available in specific mathematical fields, and their productivity could also rise significantly from the exposure to the new ideas and theorems that the Soviet émigrés introduced into the American mathematical community.

Put differently, the flood of new ideas and theorems could have spawned a new "Golden Age" in Soviet-style fields as the American mathematicians digested and incorporated the new information into their research. At the same time, however, the total number of mathematics faculty jobs, as well as the fraction of resources that deans and administrators allocate among the various subfields of mathematics, may be constrained over time. The sudden presence of experienced and highly productive Soviet émigrés who may compete for jobs with newly minted doctorates could then have a "crowd-out" effect on the paid research jobs that American mathematicians would have otherwise filled.

Figure 4 illustrates the net impact of these conflicting forces on the average number of papers published by two distinct types of American mathematicians: those mathematicians whose pre-1990 work indicated little interest in Soviet-style topics, and those mathematicians whose pre-1990 work indicated substantial overlap between their research interests and the Soviet research program.

The figure clearly shows that prior to 1990, the highly exposed group had a slight upward trend in the average number of papers published per year, while the least exposed group had a slight downward trend. After 1990, however, there is a precipitous decline in the publication rate of the group whose research agenda overlaps most with the Soviets. These differences, in fact, imply that the supply shock reduced the productivity of the exposed American mathematicians by around 25 percent. It is important to emphasize, however, that there could have been sizable beneficial spillover effects despite the observed decline in productivity. The data simply indicate that the beneficial spillover effects, if they do exist, were swamped by the adverse productivity effects resulting from the tighter availability of limited resources.

IV. Channels of Productivity Effect

The adverse net productivity effect documented in Figure 4 can operate through a large number of channels and, as noted above, could be masking a potentially sizable beneficial spillover effects. As a result, it is crucial for these types of "case studies" to look deeper into the data and try to isolate the various channels through which the supply shock can influence productivity.

1. *Fewer Citations*. Research productivity need not only be measured by a count of how many papers a mathematician publishes. A conceptually more important measure would determine whether the published work contributed to the body of mathematical knowledge, perhaps by measuring the extent to which fellow mathematicians have cited a particular paper. In fact, it turns out that the archival data also documents that the number of citations received by a post-1992 paper published by the most exposed American mathematicians declined by about a third. In other words, not only did the mathematicians most likely to be affected by the supply shock publish less, but, on average, the papers they published attracted less professional attention.

2*. Fewer Home Runs.* The average impact on productivity, regardless of whether it is measured in terms of papers or citations, masks the possibility that the impact of the supply shock might be very different at the tails of the skill distribution, and particularly at the upper tail. The policy inferences that can be drawn from the Soviet influx would be dramatically different if in addition to the adverse average effect, for instance, there was also documented evidence of substantial gains for "superstar" mathematicians. Specifically, was there an increase in the probability that the most exposed mathematicians wrote a paradigm-changing paper after 1992? The data, however, strongly show that the likelihood that an American mathematician would write a "home run" after 1992 (defined as a paper that was in the 95th or 99th percentile of lifetime citations) declined dramatically for the most exposed American mathematicians.

3. *More Coauthorships*. Elite institutions hired many of the émigrés, and these émigrés quickly began to coauthor with their American colleagues. The coauthorship rate was 5.7 percent among highly exposed American mathematicians, and rose further to 8.0 percent among the highly exposed mathematicians affiliated with the top 25 institutions. It is possible that there could be a substantial productivity gain among the American coauthors. In fact, the post-1992 decline in the probability of hitting a home run disappears entirely if one focuses on the select group of American mathematicians who coauthored with an émigré. However, the data simply indicate that the probability of hitting a home run remained constant for the American coauthors, rather than showing any sign of an increase in the probability of writing paradigm-changing papers.

4. *More Retirements*. There were also productivity effects at the other tail of the quality distribution. It turns out that there was a much greater probability of "retirement" among the most exposed mathematicians (where retirement indicates that the mathematician stopped publishing altogether). Moreover, the adverse impact of the Soviet

supply shock on the "survival rate" was particularly strong among younger (and likely untenured) American mathematicians. Not surprisingly, young American mathematicians without job security in the academic sector were particularly prone to disappear from the "publications market" as a result of the additional job competition.

5. *More Job Turnover*. In addition to an increased probability of "retirement," many of the affected American mathematicians witnessed a substantial decline in the quality of their professional affiliation. In particular, the most exposed American mathematicians, and particularly those exposed mathematicians initially employed by institutions that hired a Soviet émigré, had a far greater chance of moving to another institution after 1992, and this move typically led to a lower-quality institution. Put differently, the American mathematicians with the most Soviet-like research agendas suddenly found themselves in volatile jobs and ended up moving to lower-ranking institutions at dramatically higher rates. This type of job mobility curtailed the opportunities for the affected mathematicians to devote their time and effort to research activities that could culminate in publications.

In sum, the archival data collected by the American Mathematical Society clearly indicates that the typical American mathematician whose research agenda most overlapped with that of the Soviets suffered a reduction in productivity after the collapse of the Soviet Union. The data also reveal that these American mathematicians became much more likely to switch institutions; that the switch entailed a move to a lower quality institution; that many of these American mathematicians ceased publishing relatively early in their career; and that they were less likely to publish a "home run" after the arrival of the Soviet émigrés. There is little evidence to suggest that any benefits from positive productivity spillovers accrued to a large segment of the American mathematical community. Of course, mathematicians who could no longer remain in research settings may have entered finance or management, and our data does not measure their productivity once they leave the research arena. But, presuming that economic actors enter the sector in which they have a comparative advantage, involuntary exit from research is unlikely to improve these ex-mathematicians' productivity relative to a counterfactual in which they would have remained in their chosen careers.

V. Cognitive Mobility

If high-skill immigration changes economic opportunities in the receiving country, it seems reasonable to suspect that the most affected native workers will react to the changed environment. In fact, those reactions will provide independent information about the magnitude and direction of the changed economic opportunities. Suppose, for example, that spillover effects greatly increase the productivity of native workers in the economic sectors most heavily targeted by high-skill immigrants. We should then observe natives moving to those areas, jobs, or occupations that now offer greatly improved opportunities. If, in contrast, high-skill immigration generates adverse competitive effects in the targeted sectors, we should observe natives moving in the opposite direction, as they try to escape the worsened economic opportunities. In short, by documenting the magnitude and direction of flows of native workers that occur in response to a high-skill supply shock it is possible to determine if the net economic impact of that particular shock was beneficial or harmful.

It is useful to think of the range of possible native reactions in a much broader context when discussing the impact of high-skill immigration. After all, workers not only move from one job to another or from one geographic location to another in response to supply and demand shocks. High-skill workers will also move in the more abstract space of ideas. A scientist researching one question may respond to a demand or supply shock by shifting their effort and time to other questions instead. If each scientific question represents a "location" in a space of ideas, then *cognitive mobility* measures the movement from one location to another location in idea space.

By examining the impact of the Soviet supply shock on the choice of topics that American mathematicians pursue, it is then possible to document independently the productivity repercussions of this particular high-skill influx. The direction in which scientists move in the space of ideas should depend on whether positive spillover effects or negative scarcity constraints dominate. If beneficial spillovers dominate, mathematicians will gravitate to topics that are now in the midst of a knowledge renaissance. If competitive effects dominate, mathematicians will gravitate to topics where they would expect to find less Soviet competition. This means that we can work backwards from empirical observation of the direction of cognitive mobility to a determination of the relative strength of human capital spillovers.

To illustrate, suppose that a mathematician's location in idea space is determined by the ideas he is addressing in his current project. Once he has completed his current project, he starts another "preparation spell" that ends with the publication of his next paper, and so on. After completing each paper, the mathematician calculates the costs and benefits of staying on the same topics versus moving on to new ideas. What makes a location in idea space attractive is anything that increases the productivity of mathematicians who reside there. When a supply shock increases the number of mathematicians and theorems in one area of idea space but not in others, the shock immediately makes some locations more attractive and others less so. The supply shock may increase the productivity of mathematicians who choose to reside near it: after all, new theorems provide fresh building blocks for new results. However, the supply shock may also decrease the productivity of mathematicians who choose to reside near it: the increased competition for resources in that particular location of idea space will lower productivity.

Even if a new location in idea space becomes much more attractive, however, a mathematician will not move there if the "mobility costs" are high. One example of such a cost is the extra time that it takes to learn new methodologies and to prove theorems in an unfamiliar area. The existence of substantial mobility costs, therefore, implies that any mobility we do observe must have had net benefits or net losses associated with it that exceeded those costs. Put differently, an observation of cognitive flows towards or away from Soviet-style fields must imply that either the net benefits or the net losses are substantial simply because such moves are costly and the moves would not be worth taking if the net impact was relatively small.

It turns out that the supply shock of Soviet mathematicians and ideas did induce substantial cognitive mobility flows. We can see this easily by categorizing paper topics into two groups: Soviet-style versus American-style. Some pre-existing American mathematicians wrote their dissertations in Soviet-style fields, while others wrote in fields that did not interest the Soviets (which we call American-style fields for expositional convenience). If the Soviet shock induced cognitive mobility flows, then the probability of continuing to write in one's dissertation field should have evolved differently before and after the shock and across these two groups.

Figure 5 illustrates the trend in the cognitive mobility rate: the probability that a paper written at any point during the mathematician's career is in a different field than the dissertation. Before the Soviet Union collapsed, U.S. mathematicians who did not write a dissertation on Soviet-style topics had a 20 percent probability of writing in a Soviet-style field later on. After the shock, this probability, in fact, slightly declined. American mathematicians who did write a dissertation on Soviet-style topics had a 30 to 35 percent probability of writing papers in an American-style field later on. However, this probability increased dramatically to about 50 percent after 1992. This evidence suggests that the Soviet supply shock increased the rate of cognitive mobility *out of* Soviet-style areas of idea space. In particular, the cognitive mobility flow was in the direction of locations in idea space that received fewer Soviet immigrants.

In fact, not only is there evidence that pre-existing mathematicians moved away from Soviet-style topics, but there is also evidence that new mathematicians stayed away from those same topics as well. After all, the same economic forces that drive the research topic choices of mathematicians who were "in business" prior to 1992 will also influence the topic choices of new entrants into the American mathematics market. Put differently, the choice of a dissertation topic provides additional independent evidence about which effect is stronger: competitive effects or knowledge spillovers. If competitive effects are stronger, then fewer graduate students will specialize in Soviet-style fields; if knowledge spillovers are stronger, then more graduate students will specialize in Soviet-style fields.

It turns out that the fraction of dissertations pursuing a Soviet-style topic was about 32 percent until the time of the Soviet shock. As soon as the shock began, the fraction of new American dissertations written in Soviet-style fields began to decline, and continued to decline until 2007. By 2007, only 22 percent of new American dissertations were in Soviet-style fields.[4]

The cumulative weight of the evidence, therefore, is clear: The productivity of competing American mathematicians fell in the aftermath of the Soviet supply shock, and these productivity shifts provoked a set of reactions that are consistent with the notion that the impact of the supply shock was dominated by the adverse competitive effects. In fact, it seems sensible to presume that the affected American workers will react along *many* different margins to any high-skill supply shock, with cognitive mobility being just one of these reactions. It seems reasonable to suspect that these adjustments are likely to be an important part of any story that attempts to evaluate the economic impact of high-skill immigration.

VI. Aggregate Impact

An important implication of economic models of immigration is that immigration not only has a distributional impact, but also leads to an expansion of the aggregate economic rewards accruing to the native population. Simulations of these models, however, uniformly imply that the net gain, which is often called the "immigration surplus," is relatively small if human capital spillovers do not play an important role, often on the order

[4] Although this decline in the number of Soviet-style dissertations could reflect the impact of adverse competitive forces, it is also possible that they reflect a "fad" in the mathematics profession; perhaps it suddenly became fashionable to pursue different types of research topics in the 1990s. It turns out, however, that the decline in the number of Soviet-style dissertations was far greater among new mathematicians in the United States than among new mathematicians produced elsewhere.

of around 0.2 to 0.3 percent of national income (or about $35 billion in the context of a $15 trillion economy).[5]

It is important to note, however, that existing "estimates" of the immigration surplus are not statistics in the sense that they are calculated from real-world comparisons of how immigration affects economic opportunities for various groups of the population, but rather they are simulations of a specific model of the labor market. The Soviet supply shock and the archival data detailing the professional career of mathematicians provides a unique opportunity to actually *calculate* what happened to aggregate output in the American marketplace for mathematical ideas after the Soviet influx. Put differently, did the total number of papers published by the cohort of pre-existing American mathematicians rise or fall as a result of the Soviet influx? Equally important, did the size of the American "mathematics pie" expand or contract after we take account of the contribution of Soviet émigrés?

It is easy to conduct this exercise by examining the publication record of three distinct groups of American mathematicians: those with a pre-1990 research agenda that was highly correlated with that of the Soviets, those with an agenda that was almost uncorrelated, and everyone else. For each of these groups, we can use their pre-1992 rate of publication to predict how much they would have published after the Soviet supply shock, and we also observe how much they actually published after 1992. We can then add up the predicted and actual number of publications and determine what happened to the size and distribution of aggregate output after the supply shock. Figure 6 illustrates the

[5] Borjas (2014) summarizes the available estimates of the immigration surplus.

impact of the collapse of the Soviet Union on the aggregate output of American mathematicians.

Not surprisingly, the exercise reveals dramatic differences among the various groups of mathematicians in how well the pre-1992 productivity history predicts the post-1992 output. Consider, for example, the group of mathematicians whose work was least correlated with that of the Soviet research program. Based solely on their pre-1992 product, we would expect these mathematicians to publish 901 papers annually after 1992. In fact, this group published 1,253 papers. It seems, therefore, that the Soviet supply shock led to a slight increase in the total product of this group.

But the prediction is much further off the mark for mathematicians whose work was highly correlated with the Soviet research program. Their pre-1992 publications history predicts that they would publish 5,062 papers annually after 1992, but, in fact, they only published 4,015 papers, a "loss" of over 1,000 papers. Note, however, that once we add in the Soviet contribution of 371 papers published annually, the total size of the pie is essentially the same that we would have predicted had the Soviet supply shock never occurred. The pre-1990 publication history of pre-existing American mathematicians would suggest a total of 9,482 papers published annually between 1992 and 1999. There were, in fact, 9,245 publications.

The key lesson is that the Soviet influx caused the pre-existing American mathematics community to produce a smaller total product, and that the Soviet émigrés produced approximately enough to "fill in" the gap. Notably, we have been unable to find any evidence that the Soviets greatly increased the size of the pie.

Another possibility is that the Soviet influx improved the "quality" of American mathematics in a broader sense. We can evaluate this hypothesis by redoing the same prediction exercise with citations instead of papers. Once again, we find that pre-existing American mathematicians earn fewer citations, and that the new citations produced by the Soviet émigrés filled in the gap.[6]

In sum, we do not find any evidence to support the conclusion that the American mathematics "pie" increased in size or quality due to the Soviet supply shock. This is surprising because the relative importance of American mathematics clearly increased greatly in size and quality from around 1900 until at least the 1970s. While the demand for academic research can and has responded to new challenges and opportunities in the past, it appears that this demand was completely inelastic in response to one of the greatest challenges and opportunities of recent years. During the time period of the Soviet supply shock, there were surprisingly small year-to-year changes in the total number of mathematicians working in U.S. research institutions.[7] With the total number of research jobs unresponsive to the opportunities created by the Soviet influx, the entry of experienced Soviet mathematicians had particularly adverse effects on untenured and/or marginal mathematics faculty. Some of those faculty moved to lower-ranked institutions and some of them moved out of the academic market altogether. Regardless of their final

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[6] One alternative way of potentially measuring the trend in American mathematical output is by tracking the share of world mathematical output produced by the United States over time. The data clearly show that this share was roughly constant between 1984 and the time of the Soviet supply shock, but declined substantially thereafter. It is obvious, however, that many other factors beyond the collapse of the Soviet Union contributed to the declining importance of American productivity in the 1990s.

[7] As Borjas and Doran (2012) note: "For instance, between the 1990-91 and 1994-95 academic years, the total employment of doctoral full-time faculty in mathematics departments of Ph.D.-granting institutions increased from 6,008 to 6,147. The number of such faculty at the 82 institutions with a Conference Board of Associated Research Councils Rank of I or II (i.e., those institutions that produce the bulk of the best research) actually decreased from 3,740 to 3,613."

placement, many of these mathematicians found it increasingly difficult to do the type of research that led to publishable output, either because of an increased teaching load, fewer networking possibilities, or because the responsibilities of a job as a "quant" in Wall Street limited the kind of effort required to develop publishable material. In other words, the evidence allows for a plausible case that the Soviet supply shock mainly affected the American mathematics market by replacing some proofs that would otherwise have been proven with a roughly similar number of equally interesting theorems.

VII. Conclusion

Foreign-born scientists are an important component of the U.S. scientific workforce. Many observers cite the fact that immigrants are over-represented in scientific research as evidence that American science would benefit from increased immigration rates of high-skill workers. But the fact that a high portion of our scientific workforce is foreign-born does not by itself tell us what would happen to American science if immigration rates of scientists were lower or higher. To determine the causal impact of a change in immigration rates, we need to examine specific examples of large shifts in high-skill immigration and use state-of-the-art econometric techniques to determine what would have happened had these changes not occurred.

This paper summarizes the evidence provided by the most recent large-scale increase in immigration into the American scientific labor market: the influx of many world-class Soviet mathematicians into the U.S. workforce after the collapse of the Soviet Union. We exploit the fact that, prior to the collapse, Soviet mathematicians had specialized in some fields but not in others. This allows us to compare the outcomes of American mathematicians who could collaborate and compete with Soviets working on similar topics to the outcomes of American mathematicians whose work was unrelated to Soviet interests.

The evidence consistently indicates that American mathematicians did not experience large net beneficial productivity spillovers from the Soviets. Instead, American mathematicians voluntarily (and involuntarily) chose to work on different topics in response, and were crowded out from both the labor and publications market. The aggregate impact on the total mathematical output produced by the United States was at best roughly constant, with the Soviet mathematicians filling in the gap left open by the smaller publication rate of American mathematicians.

It is crucial to emphasize that this result does not by itself lead to straightforward policy conclusions. First, the evidence suggests that a small group of influential American mathematicians (specifically, mathematicians in high-ranked institutions who began to collaborate with the Soviet émigrés) may have benefitted from the shock.[8] It is hard to determine if the benefits accruing to this small group outweigh the losses incurred by the average American mathematician. Second, American mathematicians who changed their research focus after the shock may have fertilized other fields of science in ways that are not easily identifiable using the available publication data.

Finally, we have focused on "science" as a public good: the production of knowledge codified in research papers that are available to all scientists with access to a library, and whose ideas are reusable by anyone without licensing requirements or risk of litigation.

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[8] Borjas and Doran (2015) suggest that net positive spillovers are most likely to exist among coauthors. Freeman and Huang (2014) show that coauthorship happens more frequently among people of similar ethnic background, and Kerr and Lincoln (2010) show the importance of ethnic diasporas for harnessing the benefits of high-skill immigration. Taken together, these results suggest the need for more research on what could induce greater collaboration during a high-skill immigration shock, so that potential spillovers could be more widely spread out among native workers.

But scientific output also includes the production of (temporarily) private goods, such as patents. Moser, Voena, and Waldinger (2014), in fact, find that fields of U.S. chemistry fertilized by German Jewish immigrants in the 1930s experienced greater growth in native patenting than fields not fertilized by immigrants, raising the possibility that the Soviet supply shock could perhaps have had very different impacts had the new mathematicians been hired by private firms that could more easily respond to the changes in economic opportunities.

There is, however, one obvious institutional factor suggesting that the consequences of the migration of German Jewish immigrants in the 1930s could differ from those of the influx of Soviet mathematicians. The U.S. chemistry academic community in the 1930s was of mediocre quality, and this community was suddenly exposed to an influx of world-class scientists. The pre-existing conditions are not the same in the context of 1990s American mathematics. The world-class Soviet mathematicians entered an already world-class American mathematical community. It may be that the law of diminishing returns also applies to highly skilled labor inputs: even this particular factor of production also becomes marginally less useful when it is already plentiful. It seems prudent, therefore, to conclude that we simply do not know whether the evidence from the Soviet supply shock would have been different if mathematical output were mainly produced by the private sector.

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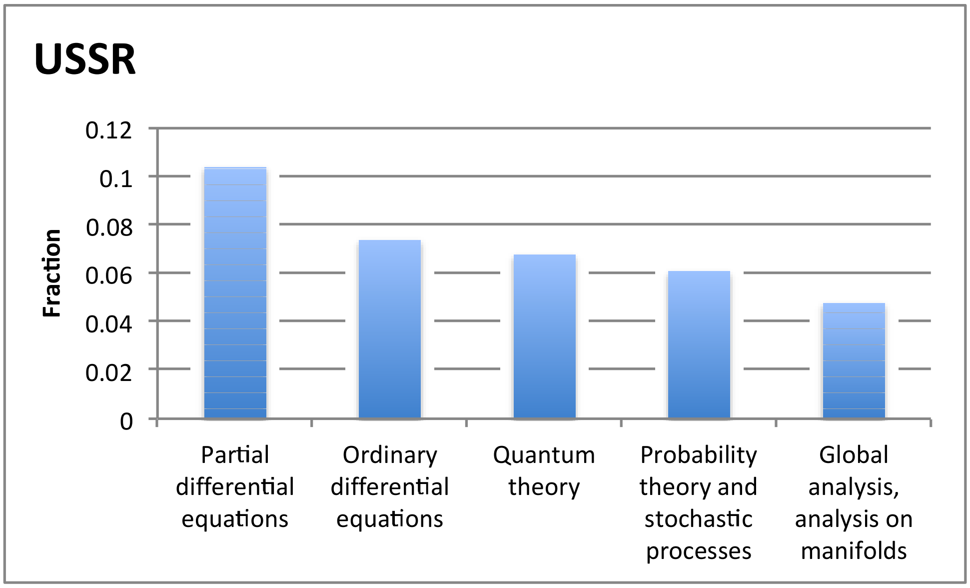
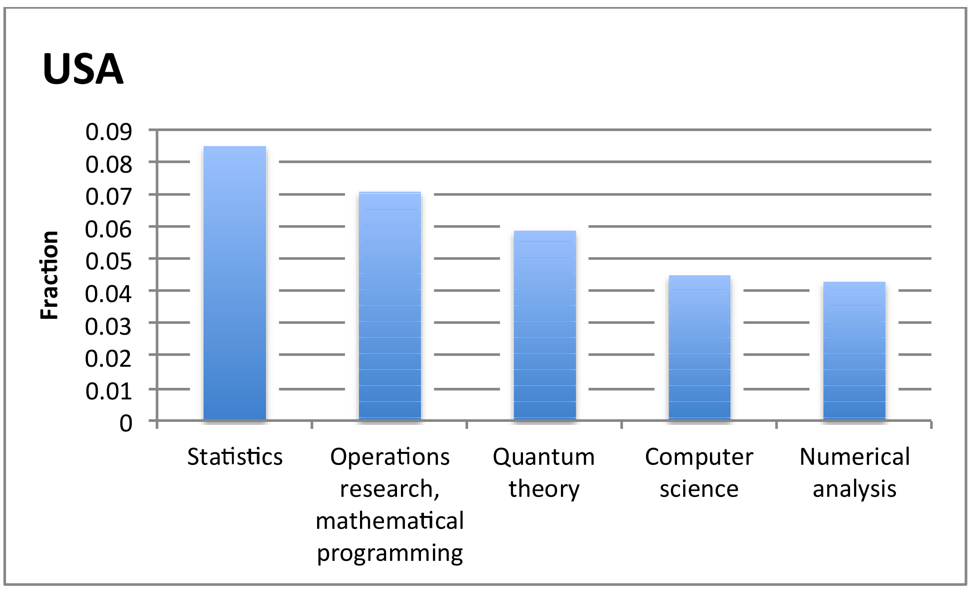
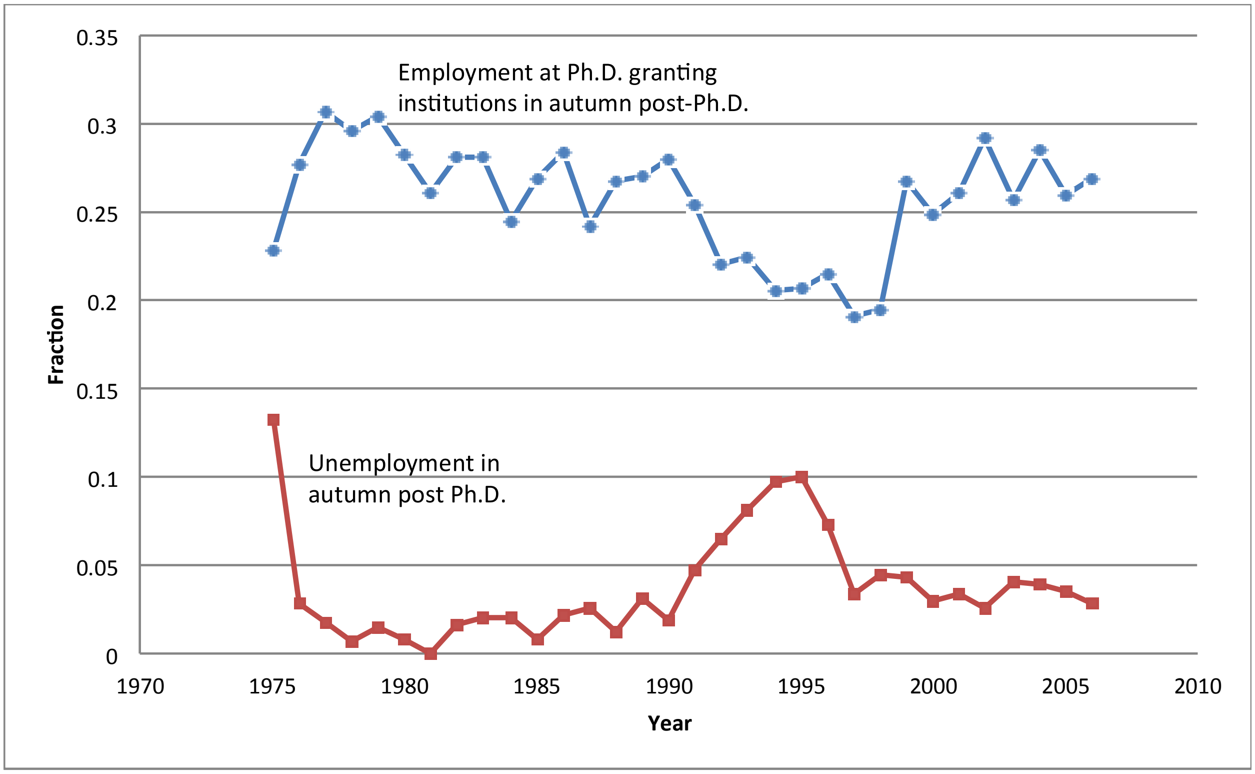
Figure 1: Five largest fields of specialization in the Soviet Union and the United States





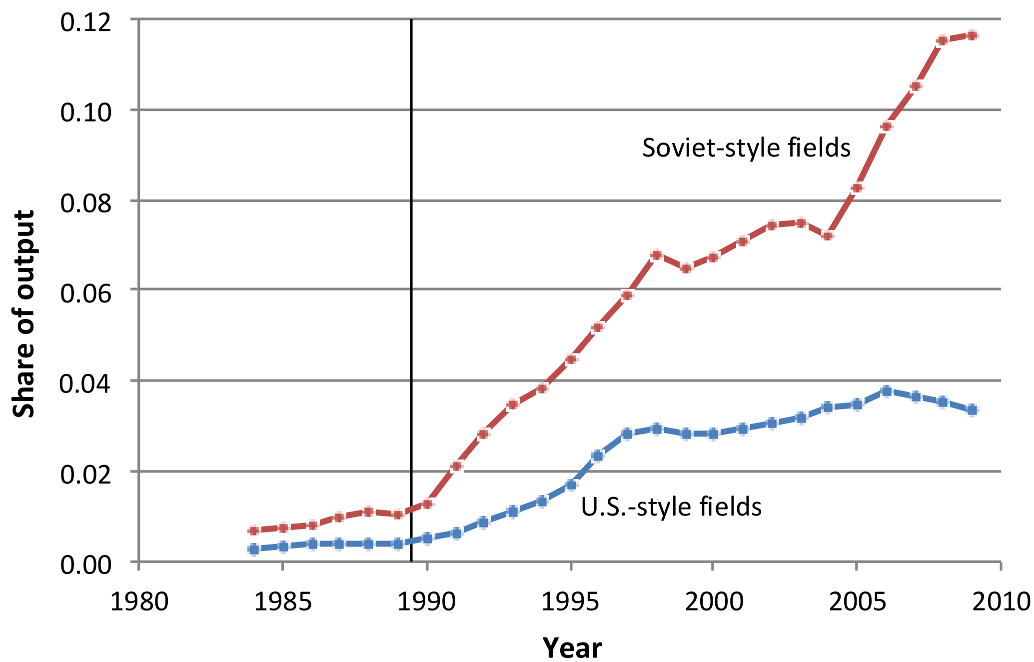
Notes: The data is compiled from the American Mathematical Society's Math Reviews database. It consists of all papers published by authors with either an affiliation in either the USSR or the US, respectively, from 1984 through 1989.

Figure 2: Employment and unemployment rates of new North American mathematics doctorates



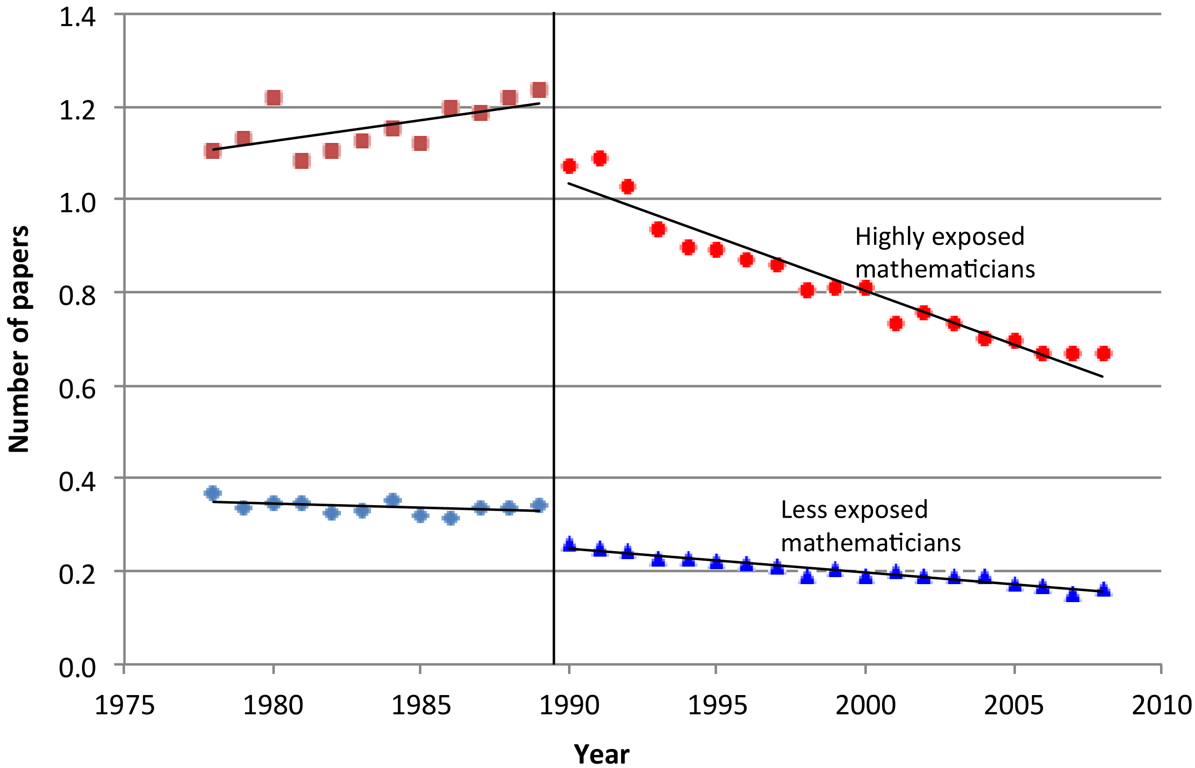
Source: Borjas and Doran (2012, p. 1154).

Figure 3. Fraction of publications published by Soviet émigrés, by type of field



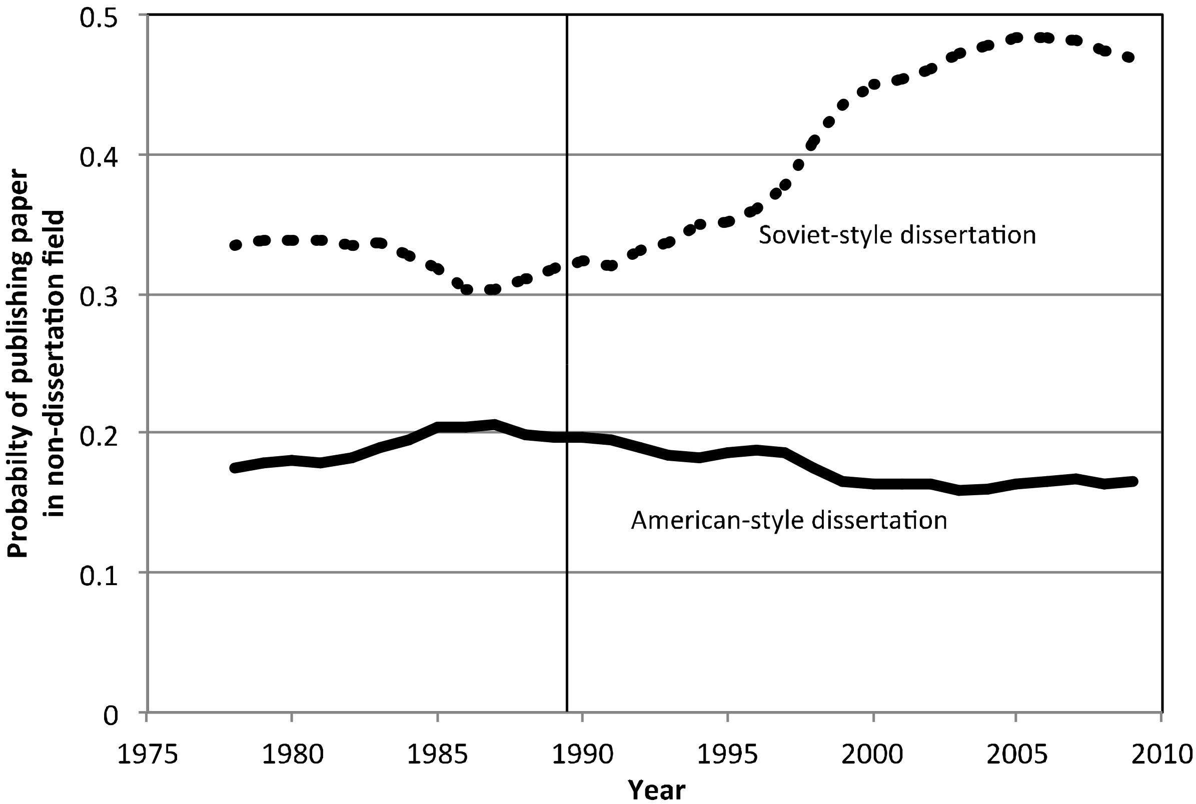
Source and notes: Borjas and Doran (2012). The U.S.-style fields consist of the 10 fields with the highest ratios of pre-influx American papers to pre-influx Soviet papers, while the Soviet-style fields consist of the top 10 fields with the lowest ratios.

Figure 4: Effect of the Soviet Supply Shock on Papers Published Per Year



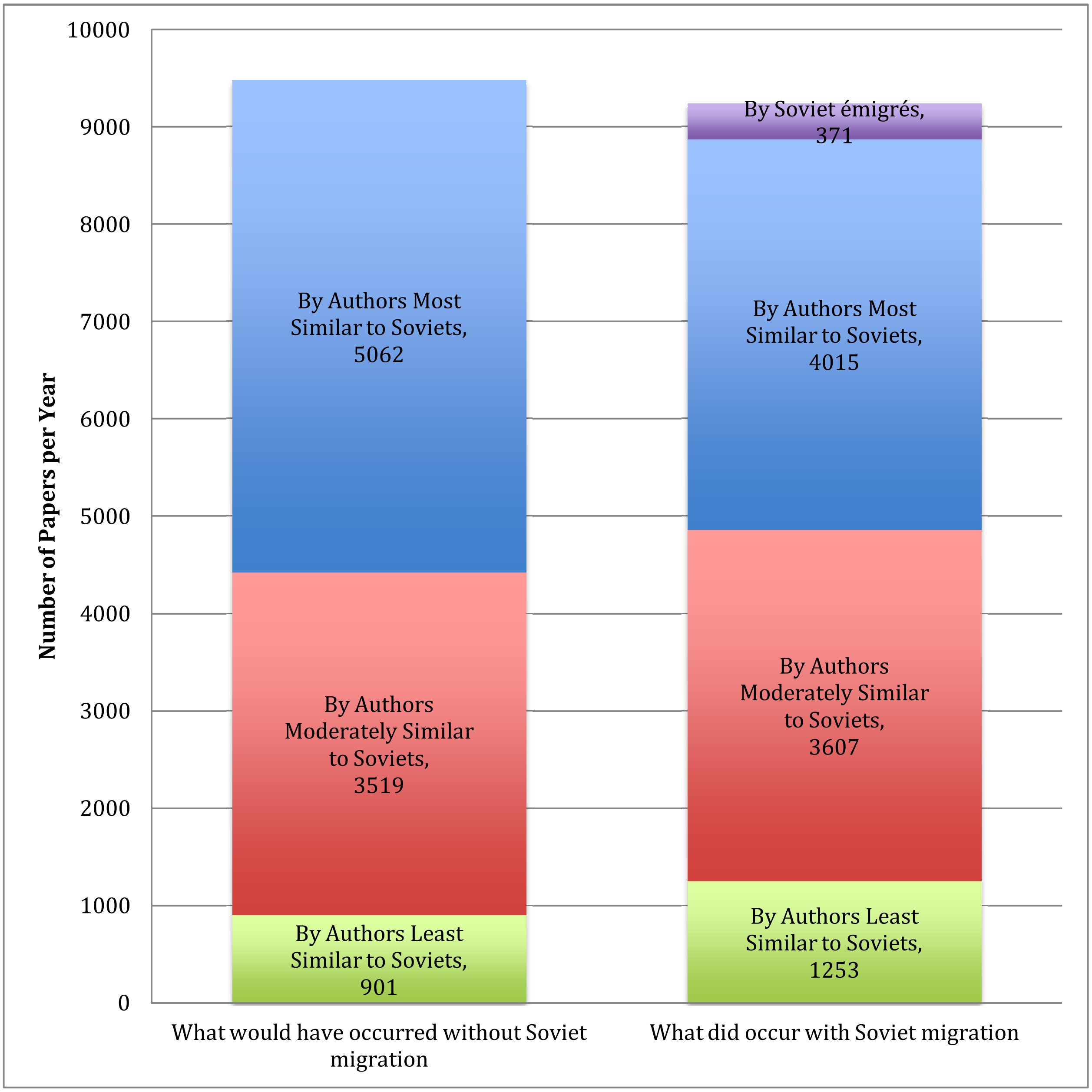
Source: Borjas and Doran (2012, p. 1172).

Figure 5: Effect of the Soviet Supply Shock on Cognitive Mobility



Source: Borjas and Doran (2014).

Figure 6: Total Annual Papers Published by Mathematicians in the United States, 1992-1999



Source: Borjas and Doran (2012, p. 1189).