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Frontier Knowledge and the Creation of Ideas: Evidence from the Collapse of International Science in the Wake of World War I

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Frontier Knowledge and the Creation of Ideas: Evidence from the Collapse of International Science in the Wake of World War I

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Abstract

We quantify how access to frontier knowledge affects the creation of ideas. We show that citing frontier knowledge is correlated with producing high-quality papers. Because this correlation may be driven by unobserved factors, we identify the causal effect of frontier knowledge by analyzing a sudden collapse of international scientific cooperation. We show that World War I and the subsequent boycott against Central scientists severely reduced the dissemination of international knowledge, including knowledge at the scientific frontier. We then estimate how the reduction of international knowledge flows affected the productivity of scientists. Specifically, we compare productivity changes for scientists who relied on frontier knowledge from abroad, to changes for scientists who relied on frontier knowledge from home. After 1914, scientists who relied on frontier knowledge from abroad published fewer papers in top science journals and produced less Nobel Prize-nominated research. Our results indicate that access to the very best research, the top 1%, is essential for scientific progress.

The creation of ideas is crucial for scientific progress, technological innovation, and economic development, particularly in a world where "knowledge has taken over much of the economy" (Economist, 2000). As argued by many scholars (e.g. Arrow, 1962, Mokyr, 2002), one of the major inputs in the

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creation of new ideas is existing knowledge. At the heart of theoretical models of endogenous growth, for example, is an ideas sector that builds on existing knowledge to produce new ideas (e.g. Romer, 1986, 1990; Jones, 1995; Weitzman, 1998). Scientists have always understood that access to existing knowledge is crucial for scientific progress. Most famously, Isaac Newton wrote in his letter to Robert Hooke that:

> "If I have seen further, it is by standing on ye shoulders of Giants." [Newton, 1675]

The quote emphasizes the value of knowledge produced by scientific "giants," i.e. frontier knowledge, for the generation of groundbreaking ideas. In fact, scientific papers that cite frontier research have a much higher probability of becoming a "hit," i.e. becoming highly cited by other researchers. Papers that cite top 1% research have a 2.1 percent chance of becoming a hit. Papers that cite top 5% research have a 1.4 percent chance of becoming a hit. Papers that do not cite frontier research, however, only have a 0.5 percent chance of becoming a hit (Figure 1).[1] Hence, compared to papers that do not cite frontier research, papers that cite top 1% research are four times more likely to become a hit.

While the figure shows that citing the research frontier is *correlated* with writing hit papers, it is not clear whether access to the research frontier has a *causal* effect on the production of high-quality ideas. The correlation could be driven by networks of highly productive scientists, who mostly cite each other, such as the physicists who advanced the quantum revolution in the 1920s and 30s. Because of this and other endogeneity concerns, researchers have not been able to empirically estimate the causal effect of frontier knowledge on the creation of ideas.

To understand the causal effect of frontier knowledge on scientific production, we investigate a historical episode of reduced international knowledge flows during and after World War I (WWI). In the second half of the 19th century, science became increasingly international, in particular during the years leading up to WWI – the so-called "golden age of internationalism in science" (Crawford 1988). With the beginning of the war in 1914, the scientific world collapsed into the Allied (UK, France, later the United States, and a number of smaller countries) and Central (Germany, Austria, Hungary, Ottoman Empire, Bulgaria) camps. Suddenly, scientists from Allied countries faced much higher costs of accessing knowledge from Central countries; particularly from Germany, a country whose scientists had received more than 40 percent of Nobel prizes in physics and chemistry in the pre-war period. Similarly, scientists from Central countries faced much higher costs of accessing knowledge from Allied countries; in particular from the UK (20 percent of Nobel prizes), France (15 percent of Nobel prizes), and the rising scientific superpower, the United States.

All major countries enlisted some of their best chemists to develop chemical weapons. The involvement of scientists in the war effort and the extremely nationalistic stance taken by many scientists in support of their homeland – Germany in particular – embittered the scientific camps

[1] See Appendix C for details on the construction of this figure.

and pitted them against each other. To punish the scientific community in Central countries for its aggressive support of the war, Allied scientists organized a boycott against Central scientists that lasted from the end of the war until 1926.

WWI and the subsequent boycott reduced access to foreign journals and international conferences. We collect data on delivery dates of international scientific journals received by the Harvard library to show that arrival delays increased substantially during this period. The delay of German journals increased from about 23 days in the pre-war period, to more than 600 days during the war, to around 150 days in 1919, to around 68 days in 1921 and 1923, and then recovered to around 28 days by 1927. The arrival delay of foreign journals from Allied countries also increased markedly during the war, but much less than for the German journals. We also collect data on international scientific conferences and document that during WWI the majority of conferences were canceled and during the boycott scientists from Central countries were banned from attending.

To quantify the reduction in international knowledge flows, and to measure how this reduction affected scientific progress, we collect data from various historical sources. First, we digitize more than 60,000 individual records from *Minerva – Handbuch der Gelehrten Welt*, the most comprehensive world-wide listing of university professors for this period, and compile two censuses of all university scientists in the world for the years 1900 and 1914. Second, we collect data on all scientific publications, including references, in 161 leading science journals from the *ISI Web of Science*, for the years 1900 to 1930. Third, we collect data on all Nobel Prize nominations for the years 1905 to 1945 from the Nobel archives.

We use these data to show that international knowledge flows, as measured by relative citations in scientific papers, were severely interrupted during WWI and the boycott against Central scientists. After 1914, papers contained fewer references to recent research produced *outside* the camp, relative to research produced at home (i.e. Allied papers contain fewer references to Central research, and Central papers contain fewer references to Allied research). We estimate that citation shares to research from *outside* the camp fell by 0.22, a decline of about 85 percent. We also show that during WWI and the boycott, international knowledge flows *inside* the camp declined, but less than across camps. We estimate that relative citation shares to research from inside the camp fell by 0.07. Overall, science became much more insular during this period, especially during WWI and the early boycott years. Moreover, we show that the reduction in international knowledge flows not only affected average research but also impacted very high-quality research, the research taking place at the frontier of scientific endeavor. Further results suggest that the fall in citations to research produced by foreign authors was predominately driven by a fall in supply of foreign knowledge (i.e. not having access to foreign knowledge), rather than by a fall in demand for foreign knowledge (i.e. having access to foreign knowledge but not citing it).

We then investigate how this fall in international knowledge flows affects scientific productivity. Specifically, we compare yearly productivity changes of scientists in field-country pairs who relied heavily on frontier knowledge from abroad, e.g. biochemistry in the United States, to scientists in field-country pairs who relied on frontier knowledge from home, e.g. biology in the United States. After 1914, scientists who relied on frontier knowledge from *outside* the camp, rather than from home, published significantly fewer papers. The estimated effect implies that U.S. scientists in biochemistry published 0.1 standard deviations fewer papers per year after 1914 (i.e. 0.15 fewer biochemistry papers per year, a productivity reduction of about 30 percent), compared to U.S. scientists in biology. We also investigate relative productivity changes for scientists in field-country pairs who relied on frontier knowledge from *inside* the camp. Consistent with the smaller declines in international knowledge flows, productivity declined less for scientists who relied on frontier knowledge from inside the camp, rather than from outside the camp.

We explore how much productivity declined after losing access to top 1%, top 3%, or top 5% research. Losing access to top 1% research led to productivity reductions that were at least twice as large as those due to losing access to top 3% or top 5% research. The results indicate that access to the very best ideas, the top 1%, increase productivity and fuel scientific progress.

To estimate the effects on productivity, we control for a number of additional factors that explain productivity, such as scientist fixed effects, year fixed effects, and career age. The results are robust to various specification checks, such as excluding chemists, who may have been involved in war-related research, from the estimation sample. The results are also robust to allowing for a differential evolution of productivity in each research field and/or camp after 1914, and to restricting the productivity measure to publications that appeared in home-camp journals.

Finally, we show that losing access to frontier knowledge reduced the production of path-breaking ideas, as measured by research worthy of a Nobel Prize nomination. The probability of publishing a Nobel-nominated paper effectively fell to zero for scientists in field-country pairs who relied on frontier knowledge from outside the camp, compared to scientists who relied on frontier knowledge from home. We also count the number of Nobel Prize nominations to measure the quality of Nobel-nominated papers. The new measure allows us to distinguish papers at the highest level of scientific quality. We show that scientists who relied heavily on frontier knowledge from outside the camp produced fewer extremely high-quality papers than scientists who relied on frontier knowledge from home.

These results deepen our understanding of the scientific production function by showing that access to the knowledge frontier is essential for the creation of ideas. It has been shown that papers that combine references to a conventional set of journals and to journals that are not usually cited in the literature are twice as likely to become highly cited (Uzzi et al., 2013). Similarly, papers that cite references that have never been cited in the literature, are 50 percent more likely to become highly cited (Wang et al., 2016). More generally, human capital is more important for scientific production than physical capital (Waldinger, 2016). Star scientists are particularly important, because they affect the productivity of co-authors (Azoulay et al., 2010; Oettl, 2012; Borjas and Doran, 2015), attract other good scientists to their universities (Agrawal et al., 2014; Waldinger, 2016), attract researchers to promising research fields (Moser et al., 2014), and train PhD students (Waldinger, 2010).[2] Because the stock of existing knowledge has accumulated over time, scientists have to absorb ever more information to reach the knowledge frontier and therefore they must invest more time in training and collaborate with larger teams (Jones, 2009, Wuchty et al., 2007).

The results also speak to the literature on international knowledge flows. City, state, and country borders are important barriers to knowledge flows, as measured by patent citations (e.g. Jaffe et al., 1993; Thompson and Fox-Kean, 2005; Peri, 2005; Belenzon and Schankerman, 2013). Scientific networks are often formed through co-location, a tendency that partly explains the large effects of borders on international knowledge flows (Head et al., 2015). It has also been shown that country borders can become more or less permeable over time. While Western-to-Communist book translations were very rare during the Cold-War period, they increased massively after the Collapse of the Soviet Union (Abramitzky and Sin, 2014).[3]

More broadly, it has been shown that scientific institutions matter for the use of prior knowledge in follow-on research. Materials that have been deposited in biological resource centers that collect, certify, and distribute biological material, are more likely to be used in follow-on research, as measured by citations to papers that first use the material (Furman and Stern, 2011). Intellectual property rights increase the cost of using prior knowledge in follow-on research (Scotchmer, 1991; Williams, 2013; Murray et al., 2009; Galasso and Schankerman, 2015; Biasi and Moser, 2015). In fact, the compulsory licensing of German patents after WWI increased patenting by U.S. inventors in the 1930s (Moser and Voena, 2012).

We add to the literature by showing that borders impede knowledge flows of scientific papers, even though scientists are keen to share their discoveries so that they can be used as inputs in the creation of subsequent knowledge.[4] We also show that political events affect how much borders obstruct international knowledge flows. Moreover, we exploit changes in international knowledge flows to estimate the causal effect of access to scientific knowledge on the productivity of scientists. Our results show that access to the very best research, the top 1%, is essential for the creation of path-breaking ideas and scientific progress.

[2]Other research has shown negative effects of stars on incumbent mathematicians after the migration of mathematicians from the Soviet Union to the United States, a situation where journal and faculty slots are fixed (Borjas and Doran, 2012). Similarly, star scientists do not seem to have a positive effect on their peers in the same department (Waldinger, 2012; Agrawal et al., 2014, Borjas and Doran, 2015). New evidence on high-skilled individuals in private sector firms suggest similar effects on collaborators and localized peers (Cornelissen et al., 2013, Jaravel et al., 2015).

[3]A related literature on open access of scientific journals shows that open access does not significantly increase citations to openly accessible articles in most cases (Davis et al., 2008; McCabe and Snyder, 2015), even though other papers find small positive effects of open access (McCabe and Snyder, 2013). Open access, however, increases citations from poorer countries (Evans and Reimer, 2009; McCabe and Snyder, 2015).

[4]Citations by follow-on research are an important element of recognition and serve as a measure of achievement within the scientific community and affect the rewards to scientists. This is in contrast to technology, where knowledge is often kept private through patenting or secrecy (Merton, 1957; Dasgupta and David (1994); Stephan, 2010).

1 A Shock to International Scientific Collaboration

1.1 Brief History of Science Around WWI

Science before WWI

Science became increasingly international during the second half of the 19th century, and in particular in the years leading up to WWI – the so-called "golden age of internationalism" in science (Crawford, 1988). Scientists published their most important contributions in international journals, conferences became more international, and scientific societies increased international collaboration. In 1899 the leading scientific nations founded the *International Association of Academies* to "facilitate scientific intercourse between the different countries" (Greenaway, 1996). To improve access to scientific knowledge, the Royal Society, the oldest scientific society in the world, coordinated the publication of the *International Catalogue of Scientific Literature,* which translated the title of almost every scientific paper into English, German, French, and Italian.

WWI and Science

The increasing internationalization of science was abruptly interrupted by the outbreak of WWI, at the end of July, 1914. The Western world disintegrated into two warring camps with the Allies (UK, France, later the United States, and number of smaller countries) fighting the Central Powers (Germany, Austria, Hungary, Ottoman Empire, and Bulgaria) (see Table 1). While the war caused millions of military deaths, it caused relatively few civilian deaths in the major scientific powers USA (757 deaths), UK (16,829, mostly merchant fleet), and Germany (720), because the war was not fought on the territories of these countries.

All major war participants enlisted some of the most prominent scientists to support the war effort, particularly for the development of chemical weapons. The German unit was led by future Nobel Laureate Fritz Haber, who assembled a team of the most prominent chemists to develop new poisonous gases. His team included seven future Nobel Laureates: James Franck, Gustav Hertz, Otto Hahn, Walter Nernst, Emil Fischer, Heinrich Wieland, and Richard Willstätter (Van der Kloot, 2004). The French unit was led by Victor Grignard, who had received the Nobel Prize in 1912. The United States also enlisted a number of prominent scientists, including the future president of Harvard, James Bryant Conant.

Many scientists, particularly those from Germany, took a nationalistic stance during this period and even issued statements in support of their home country's military actions. In the so-called *Manifesto of the 93*, which was widely published in October 1914, 93 German intellectuals, among them 14 science Nobel Laureates, declared their support for Germany's military actions including the killing of Belgian civilians and the destruction of Leuven with its famous university library. Two weeks later, 3,000 German university teachers endorsed a declaration that "…Europe's culture depends on the victory of the German military" (Reinbothe, 2006, p. 99). In a reply that was published in *Nature*, the British chemist and Nobel Laureate William Ramsay condemned German scientists stating that "their ideal…is to secure world supremacy for their race…" (Ramsay, 1914).

The Boycott Against Scientists from Central Countries

The participation in the war effort and the hostile attitude toward their international peers soured international scientific relations. As early as October, 1914, William Ramsay had suggested "restrictions of the Teutons" (Ramsay, 1914) for the post-war era. Just before the end of the war, Allied scientists organized a conference at the Royal Society in London, which paved the way for a boycott against Central scientists. The scientists announced that

> "…the Allied Nations are forced to declare that they will not be able to resume personal relations in scientific matters with their enemies until the Central Powers can be readmitted into the concert of civilized nations." [Quoted in Lehto, 1998, p. 18.]

At a follow-up conference in Brussels, over 200 scientists from 12 Allied countries founded the International Research Council (IRC) to organize post-war international scientific cooperation.[5] The IRC ensured that scientists from Central countries were effectively cut-off from Allied scientific associations and international scientific meetings, even if the associations or conference organizers were not officially affiliated with the IRC (Schroeder-Gudehus, 1973). While the boycott was strictly enforced in the first post-war years, its strength declined over time. In 1922, the Allied majority rejected a proposal by Neutral scientists to invite Central scientists to join the IRC (Cock, 1983, Lehto, 1998, p. 38). In the following years, the Allied position softened and the boycott was officially terminated in June 1926 (Lehto, 1998, p. 40).[6] Two years later, the eminent German mathematician David Hilbert was honored to deliver the opening address of the International Congress of Mathematicians in Bologna. He proclaimed:

> "It makes me very happy that after a long, hard time all the mathematicians of the world are represented here. This is as it should be and as it must be for the prosperity of our beloved science. It is a complete misunderstanding of our science to construct differences according to peoples and races...For mathematics, the whole cultural world is a single country." [Quoted in Reid, 1970, p. 188.]

[5] The IRC replaced the *International Association of Academies* that had overseen international scientific relations in the pre-war era. The IRC statutes explicitly excluded the former Central countries, but some formerly Neutral countries were invited to join as members (Kevles, 1971, p. 58).

[6] In June 1926, Germany, Austria, Hungary, and Bulgaria were invited to join the IRC. While the German scientific academies officially declined the invitation, the boycott was effectively terminated at this point (see results below). In 1931, the IRC was dismantled and international scientific collaboration was then organized under the auspices of the *International Council of Scientific Unions*.

1.2 The Effect on Access to International Scientific Knowledge

During the war and the subsequent boycott, the cost of accessing international scientific knowledge increased substantially; both Allies and Centrals became increasingly strict about sharing scientific knowledge with foreign countries. Access to foreign journals became restricted. Most international conferences were canceled during the war. During the boycott Central scientists were banned from attending international conferences. More generally, most efforts to foster international scientific collaboration were interrupted during this period. The publication of the *International Catalog of Scientific Literature*, for example, was discontinued after 1914.

Access to Scientific Journals from Foreign Countries

We measure how the war and the boycott reduced access to foreign journals by investigating entry stamps from the Harvard library. To register the delivery of a journal, Harvard librarians placed an entry stamp on each issue upon arrival (see Appendix Figure A.2 for an example). We collect data on these stamps for the years 1910, 1913, 1917, 1919, 1921, 1923, and 1927 for four international journals: the *Zeitschrift für Analytische Chemie*, the *Annalen der Physik*, *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, and *Nature*. We then calculate the average delay between the publication of a journal and its arrival at Harvard for each of the seven years (see Data Appendix D for details).

Before the war, the German *Zeitschrift für Analytische Chemie* arrived with a delay of about 26 days (Figure 2, panel (a)). By 1917, the delay increased to about 500 days, or nearly one and a half years. In 1919, deliveries improved but the delay remained lengthy, close to 150 days. Between 1921 and 1923, the delay was still 100 days. By 1927, the journal was delivered almost as quickly as in the pre-war period. The pattern for the *Annalen der Physik*, the German journal that published Albert Einstein's famous 1905 papers, looks similar (Figure 2, panel (a)).

We also plot delays for two Allied journals from abroad, the French journal *Comptes Rendus* and the British journal *Nature*, the leading general science journals from these countries. Before the war, the *Comptes Rendus* arrived about 21 days after publication (Figure 2, panel (b)). By 1917, the delay increased to about 45 days. By 1919, it reached 57 days, about three times longer than in the pre-war period. After 1921, the delay returned to its pre-war level. Before the war, *Nature* arrived only 10 days after publication – faster than the other journals, presumably because of shorter shipping routes from Britain. The delay for *Nature* almost tripled to 27 days during the war, and then partly recovered to about 19 days by 1921.

While the arrival delay for all foreign journals increased during the war and the boycott, the delay for German journals increased markedly more than for Allied journals (Figure 2, panel (c)).

To investigate whether the marked increase in arrival delays for German journals was caused by a general disruption of the German publishers, we compare arrival delays for the *Annalen der*

Physik at Harvard and the German University of Heidelberg (see Data Appendix D for details). Even at Heidelberg, the delay increased during the war, but the increase was nowhere near as large as at Harvard (Figure 2, panel (d)).

These patterns indicate that foreign journals, in particular those from the enemy camp, became harder to access during the war and the boycott. Moreover, because Harvard has one of the best-funded university libraries in the world, it is plausible that the delays experienced by other universities were more extensive.

Scientific Conferences

The war and the boycott also impacted international scientific conferences. In the pre-war period (1900-1914), scientists organized 443 large international congresses. During the war (1914-1918), only seven large international congresses took place (Forschungen and Fortschritte, 1933). In the post-war period, the number of international congresses was less than 20 in 1919, but steadily increased to more than 110 in 1926, and more than 165 in 1930 (Kerkhof (1940)).[7] During the boycott, Central scientists were banned from most international conferences. While this ban was most strictly enforced in the first post-war years, it continued to significantly limit conference attendance of Central scientists until 1926. Kerkhof (1940) reports that the ban on German scientists applied to all international conferences in 1919; to about 85 percent in 1920; to about 60 percent in 1921 and 1922; and to about 50 percent in 1924 and 1925. From 1926 onward, German scientists were excluded from less than 15 percent of international conferences.

We complement the historical accounts with data on attendance records of the *International Congresses of Mathematicians* (ICM), the largest mathematics conference. In the pre-war period, Germany always sent large delegations to the ICM (see Table 2, column 1). The 1916 congress that was scheduled to be held in Stockholm was canceled because of the war. The first post-war congress in 1920 was not held in Stockholm, but was relocated to Strasbourg in a symbolic move. Strasbourg lies in the Alsace region that had been annexed from France by Germany in the 1870/71 war and then had been returned to France after WWI. German mathematicians were not invited. Nor were they invited to the Toronto congress in 1924. By 1928, the boycott had ended and Germany sent the second largest delegation, after the host nation, to the congress in Bologna.

We further document that even small and very elitist conferences were affected by the war and the boycott. We analyze attendance patterns at the *Solvay Conferences* in Physics. The Nobel laureate Werner Heisenberg lauded "[t]he Solvay meetings...as an example of how much well planned and well organized conferences can contribute to the progress of science" (Mehra, 1975, p. VII). The first *Solvay Conference* was organized in 1911 and was attended by the leading physicists of the time,

[7]These figures only refer to large international congresses, such as the *International Congresses of Mathematicians* below, but not to smaller international workshops and scientific meetings. For these smaller gatherings, there are no systematic data.

including Marie Curie, Ernest Rutherford, Max Planck, and Albert Einstein (Figure 3, panel (a) and Appendix Table A.2). In that year, nine of the 24 participants came from Central countries. In 1913, nine of the 31 participants came from Central countries. During the war, the *Solvay Conferences* were discontinued. The first post-war conference took place in 1921 and Central scientists were not invited.[8] Nor were they invited to the 1924 conference. By 1927, the boycott had ended and five of the 30 participants came from Central countries.[9] (The 1927 conference, perhaps the most famous scientific conference ever organized, took place at the height of the quantum revolution and 17 of the 30 participants were current or future Nobel Laureates.) In 1930, six of the 36 participants came from Central countries.

2 Data

2.1 Censuses of University Scientists for 1900 and 1914

For our main analysis, we obtain data from various sources. First, we collect two historical censuses of all university scientists in the world for the years 1900 and 1914. The data come from two volumes of *Minerva–Handbuch der Gelehrten Welt*, the most comprehensive world-wide listing of university professors for this period. We digitize more than 2,500 pages that list university professors of all ranks (e.g. assistant professors, associate professors, and full professors) in all universities in the world (see Appendix Figure A.3 for a sample page).

The data contain information on 569 universities in the year 1900, and 973 universities in the year 1914, indicating the exceptional growth of the university sector during this period (Table A.1, panel A). Across all fields, we manually digitize the names, affiliations, and fields of 23,917 professors in 1900, and 36,777 professors in 1914 (Appendix Table A.1, panel A). Figure A.4 shows the distribution of scientists in 1914. The map illustrates the concentration of scientific activity in the United States and Western Europe.

We focus our empirical analysis on five scientific fields: medicine, biology, chemistry, physics, and mathematics.[10] During the time period studied in this paper, scientists in these fields already published the majority of their research in academic journals. The publishing process closely re-

[8] The lone German invited to the 1921 and 1924 conferences was Albert Einstein, then a professor at the University of Berlin. The invitations reflected his special status in the scientific community and his reputation as an avid internationalist. In 1921 he declined to attend for personal reasons and in 1924, he declined the invitation because none of his German colleagues had been invited (Mehra, 1975, p. XXIII).

[9] In fact, two more participants were de facto in the German system but are classified as Neutrals in Mehra's data. Heisenberg had a joint appointment at the German University of Göttingen and the Danish University of Copenhagen and moved to a permanent position at the German University of Leipzig in 1927. Schrödinger moved to the German University of Berlin in 1927.

[10] *Minerva* lists the exact specialization, often in native language, for each scientist. Many mathematicians, for example, do not report "mathematics" but "algebra" or "number theory," often in native languages, as their field. We manually recode several thousands of the exact specializations into 32 fields, such as the five scientific fields medicine, biology, chemistry, physics, and mathematics; but also all other fields like history, law, and so on.

sembled publishing in modern times. Our data contain information on 10,133 scientists in 1900 and 15,891 scientists in 1914 across the five fields (Appendix Table A.1, panel B).

2.2 Publication and Citation Data

Obtain full information on citing papers and references

We also collect all papers that were published in 161 leading science journals from the *ISI Web of Science* for the period 1900 to 1930 (see Appendix Table A.3 for a list of all journals in our data), including information on the cited references.[11] The publication and citation data have the following structure:

Citing paper	References
Citing paper 1 (full information)	reference 1 (partial information)
Citing paper 1 (full information)	reference 2 (partial information)
Citing paper 1 (full information)	reference 3 (partial information)
Citing paper 1 (full information)	reference 4 (partial information)
Citing paper 2 (full information)	reference 1 (partial information)
Citing paper 2 (full information)	reference 2 (partial information)
Citing paper 2 (full information)	reference 3 (partial information)
⋮	⋮

The *Web of Science* reports only partial information for each reference. Instead of including the full reference with all authors and complete journal information, each reference lists at most five items: the first author, the publication year of the reference, an abbreviation of the journal name, the volume of the journal, and the first page of the article.

We obtain complete references, including a full list of referenced authors, their affiliations (if available), and the total number of citations received by the reference, by merging the full information from all papers in our data with the references. To improve the quality of this match, we first correct spelling inconsistencies in the abbreviated name of the referenced journal.[12]

References abbreviate journal names, such as the *Proceedings of the National Academy of Sciences of the United States of America* (PNAS) in various ways, such as "p natl acad sci usa," "p nat ac us," and with dozens of other abbreviations. We manually standardize around 2,000 different ways of spelling the abbreviated names of referenced journals.

[11]Because the historical part of the *Web of Science* focuses on the highest cited journals, it has very good coverage of Anglo-Saxon and German journals. The coverage of French journals, for example, is less comprehensive. This does not bias our analysis because our regressions implicitly control for persistent differences in coverage across countries.

[12]References may not merge during this step for two reasons: first, the reference was not published in one of the 161 journals in our data, and second, some items in the reference are misspelled. In our sample, we obtain full information on 62 percent of recent references. Because we need to measure the country and quality of references for our analysis, we focus on papers with full reference information.

Assign countries to citing papers and references

Our analysis crucially depends on knowing the country of authors and cited references. Most historical science journals, however, did not report author affiliations. For example, Max Planck's famous 1901 paper "On the Law of Distribution of Energy in the Normal Spectrum," which is often considered to have started the quantum revolution, was published in the *Annalen der Physik* and does not include Planck's affiliation.

We assign countries to authors and references in a three step hierarchical process (see Appendix B.2 for further details). First, we use the country information from the affiliation reported in those papers that list affiliations. Second, we use the country information from the two scientist censuses.[13] Third, we expand the country information for authors with identical names within the corresponding citing or cited journal. E.g. the Nobel Laureate Arthur Compton published a paper in the *Physical Review* in 1923 that lists an affiliation in the United States. He also published a paper in the *Physical Review* in 1920 that does not list an affiliation. We then assume that the 1920 paper was also published by a U.S. author.

We use the fraction of citing authors and referenced authors from each country to assign countries to papers and their references. A paper (reference) exclusively written by authors from the United States, for example, counts as one U.S. paper (reference). A paper (reference) co-authored by one U.S. author and one U.K. author, counts as 0.5 U.S. papers and 0.5 U.K. papers (references).[14]

Mistaking an author (or reference) for another author (or reference) with the same name from the same country does not introduce measurement error because the sole purpose of this matching is the assignment of countries to authors and references. Remaining mistakes in assigning countries to papers and references will introduce measurement error. Depending on the estimated specification, the measurement error will either affect the dependent variable or the explanatory variables. With classical measurement error, our results remain unbiased in the first case and will be biased towards zero in the second case. The latter would make it more difficult to find significant effects.

2.3 Data on Nobel Prize Nominations

To measure the quality of research output, we also collect data on nominations for the physics, chemistry, and physiology/medicine Nobel Prizes from Nobelprize.org (2014). The data contain 993 individuals who received at least one nomination for a Nobel Prize between 1905 and 1945. We merge these data with the publication data from the *Web of Science* to identify research that was worthy of a Nobel Prize nomination (see section 4.2 for details).

[13]In the very rare case that two or more scientists have identical names and work in the same field but in different countries, we assign the paper proportionally to each country. E.g. the censuses contain two chemists with the name J. Schmidt, one in Germany and one in Austria. We therefore count chemistry papers published by J. Schmidt as half German and half Austrian. Note that the *Web of Science* only reports the last name and initials of each author.

[14]The country of papers and scientists is defined by a scientist's university affiliation.

2.4 Final Datasets

We combine the data to construct two main datasets: a paper-level dataset that allows us to study international knowledge flows, and a scientist-level dataset that allows us to study how the interruption of international knowledge flows affected the productivity of scientists.

The paper-level dataset covers the period 1905 to 1930 and contains all papers for which we match the country of at least one author and at least one reference, and for which we know how many times the references are cited until today.

The scientist-level dataset is a panel dataset of all university scientists who published at least one paper between 1905 and 1930. It contains yearly publication output for each scientist and an indicator of whether they produced a paper that led to a Nobel Prize nomination.

3 The Effect of WWI and the Boycott on International Knowledge Flows

3.1 Measuring Knowledge Flows

We measure knowledge flows with references in scientific papers. For each paper, we count the references that quote existing research from home, from a foreign country inside the camp, or from a foreign country outside the camp.[15] By normalizing these counts with the total number of references, we create three shares that measure knowledge flows from home ($\frac{c_{Home}}{C_{Total}}$), foreign countries inside the camp ($\frac{c_{Foreign-IN}}{C_{Total}}$), and foreign countries outside the camp ($\frac{c_{Foreign-OUT}}{C_{Total}}$).

To measure recent knowledge, we consider references to research published in the preceding five years, which we call references to recent research. The average paper in our sample includes 17.6 references overall; of these, 7.4 cite recent research and 4.6 cite recent research published in one of the 161 journals. For 3.0 of these references, we match country information and for 2.6 the *Web of Science* reports the number of times the reference was cited until today.

Figure (4) illustrates our measure of knowledge flows. A paper published by a U.S. author in year t includes four references to research published in the preceding five years; one reference to U.S. research that was published in year t, one reference to German research that was published in year t, one reference to U.K. research that was published in year $t-2$, and one reference to U.S. research that was published in year $t-4$. The corresponding shares are:

[15] We do not count self-citations when we count the references to research from home.

$$\frac{c_{Home}}{C_{Total}} = \frac{2}{4} = 0.5$$

$$\frac{c_{Foreign-IN}}{C_{Total}} = \frac{1}{4} = 0.25$$

$$\frac{c_{Foreign-OUT}}{C_{Total}} = \frac{1}{4} = 0.25.$$

Table 3 summarizes the citation shares in our sample. About 69 percent of references quote research from home, 16 percent quote research from foreign authors inside the camp (e.g. in the UK for citing papers from the United States), and about 15 percent quote research from outside the camp (e.g. in Germany for citing papers from the United States). If we consider citations to the very best research, as measured by references that quote research that ended up in the top 1% of the citation distribution, 5.4 percent of references quote top 1% research from home, 1.2 percent quote top 1% research from foreign authors inside the camp, and about 1.3 percent quote top 1% research from outside the camp.

3.2 The Effect of WWI and the Boycott on Relative Citations of Allies and Centrals

To measure changes in these shares during the war and the boycott, we create three observations per paper: the share of references quoting research from home, from inside the camp, and from outside the camp. We then investigate how these shares changed after 1914 by estimating the following regression:

$$\begin{aligned} Citation\ Shares_{ic} &= \omega_1 \cdot 1\left[c = \text{Foreign Out}\right] + \omega_2 \cdot 1\left[c = \text{Foreign Out}\right] \times 1\left[t\left(i\right) = \text{Post 1914}\right] \\ &+ \iota_1 \cdot 1\left[c = \text{Foreign In}\right] + \iota_2 \cdot 1\left[c = \text{Foreign In}\right] \times 1\left[t\left(i\right) = \text{Post 1914}\right] \qquad (1) \\ &+ \text{Citing Paper} FE_i + \epsilon_{ic}, \end{aligned}$$

where i indexes papers and c indexes camps. A home indicator is excluded from the regression. Hence, ω_1 measures how the pre-war share of references to research from outside the camp differs from the pre-war share of references to research from home. Similarly, ι_1 measures how the pre-war share of references to research produced by foreign authors from inside the camp differs from the pre-war share from home. The parameters of interest, ω_2 and ι_2, measure how the foreign shares change after 1914, relative to the home share.

The regression also includes a fixed effect for each citing paper. These fixed effects control for permanent differences in citation patterns across countries, e.g. if U.S. or German authors generally include more references to research produced at home (a U.S. fixed effect, for example, would be collinear with the sum of paper fixed effects for all U.S. papers). The paper fixed effects also control for permanent differences in citation patterns across fields, e.g. if chemists always cite more research produced at home because the chemical industry is differently specialized across countries. The fixed effects even control for permanent differences of fields in a certain country, e.g. if U.S. chemists generally cite more research produced at home. To account for a potential correlation of standard errors in a certain field-country pair, e.g. chemistry in the United States, we cluster standard errors at the field-country level.

After the onset of WWI, papers cited relatively less research from *outside* the camp. The share of references quoting research from outside the camp fell by 0.22, relative to the home share (Table 4, column 1, significant at the 1 percent level), a reduction of 85 percent relative to the pre-war share of references quoting research from outside the camp. The share of references quoting research from foreign authors inside the camp fell by 0.07, relative to the home share (Table 4, column 1, significant at the 10 percent level), a reduction of 50 percent relative to the pre-war share of references quoting research from inside the camp. The results are slightly larger, in absolute magnitude, if we include camp-specific linear trends in the regression (Table 4, column 2).

The estimated effect varies over time. The relative decline of the share of references quoting research from outside the camp was 0.22 during WWI, 0.25 during the boycott, and 0.19 in the post-boycott period (Table 4, column 3, all significant at the 1 percent level).[16] The relative decline in the share of references quoting foreign research from inside the camp was 0.11 during WWI, 0.09 during the boycott, and 0.05 in the post-boycott period (Table 4, column 3, only the first two are significant at the 1 percent and 5 percent level, respectively).

These results suggest that WWI and the boycott significantly reduced knowledge flows from abroad, particularly from countries outside the camp. The results are slightly larger if we control for camp-specific linear trends (Table 4, column 4) and are relatively similar for Allied and Central papers (Table 4, columns 5 and 6). For Central papers, the share of references quoting research from outside the camp only declined significantly during the boycott. In that period, however, the decline was larger than for Allied papers.

To get a better understanding of the timing of these changes, we estimate yearly coefficients using equation (2):

$$\begin{aligned} \textit{Citation Shares}_{ic} &= \sum_{\tau=1905}^{1930} \omega_\tau \cdot 1\left[c = \text{Foreign Out}\right] \times 1\left[t\left(i\right) = \tau\right] \\ &+ \sum_{\tau=1905}^{1930} \iota_\tau \cdot 1\left[c = \text{Foreign In}\right] \times 1\left[t\left(i\right) = \tau\right] \\ &+ \text{Citing Paper}FE_i + \epsilon_{ic}. \end{aligned} \tag{2}$$

We plot the yearly coefficients in Figure 5. Even before WWI, papers contained fewer references to recent research from outside the camp and even fewer to foreign research from inside the camp,

[16]It is important to keep in mind that we count references produced in the preceding five years for these results. For a paper published in 1927, for example, we count references to research published between 1923 and 1927.

indicating a substantial home bias (Figure 5). After the onset of the war, relative citations to research from foreign authors declined sharply, in particular citations to research from outside the camp. After 1919, citations shares began to recover but remained lower than in the pre-war period.

Citations to high-quality research

In further results, we explore whether the reduction in international knowledge flows, as measured by cited references, also affected high quality research. For this test, we focus on references that quote research that ended up in the top percentiles of the citation distribution (counting the total number of citations of each piece of research until today). Because we can measure citations over almost 100 years, this measure of the research frontier captures the very long-run view of the quality of research and should therefore not be affected by short-term scientific "fashions." [17]

The share of references to top 5% research from outside the camp fell by 0.053, relative to references to top 5% research from home (Table 5, column 1, significant at the 1 percent level), a reduction of 95 percent, relative to the pre-war share.[18] The point estimate becomes larger in absolute magnitude if we control for linear camp-specific trends (Table 5, column 2). The share of references to top 5% research from foreign authors inside the camp fell by 0.023 relative to top 5% research from home (Table 5, columns 1 and 2), a reduction of 72 percent relative to the pre-war share. The latter effect is not significant at conventional levels. Yearly coefficients are reported in panel (a) of Figure 6.

We also find that the share of references to top 3% or top 1% research from *outside* the camp fell significantly (Table 5, columns 3-6, significant at 1 percent, also panels (b) and (c) of Figure 6). The share of references to top 3% or top 1% research from foreign authors *inside* the camp also fell, but by less than the share of references to research from outside the camp (Table 5, columns 3-6, significant at 1 percent, also panels (b) and (c) of Figure 6). These results indicate that the war and the boycott also affected the dissemination of high-quality research.

Robustness

It is important to note that changes in relative quality of scientific output in the Allied or Central camp are unlikely to drive our findings, because such changes would have decreased the share of references to research from outside the camp for one of the camps, but would have increased the share for the other camp.

[17] Specifically, we divide the share of references to research from home into references that ended up in the top 5% of the distribution and references that ended up in the bottom 95%. Similarly, we divide the shares to research from inside the camp and outside the camp. Hence, the data now contain six observations per paper. Citations to top research from home are the omitted category. The top 5% is measured at the subject level for all papers in the 161 journals in our data, independently of whether we can assign countries to authors and/or references. We construct analogous measures of citations to research that ended up in the top 3% or top 1% of the citation distribution.

[18] Not surprisingly, the estimated coefficient is smaller than for all references, because the share of references to top 5% research is smaller than the share of references to research of any quality (see Table 3).

The previous results are estimated on the full sample of papers. The sample includes papers by authors with a university position by 1914 and papers by other authors if they reported a university affiliation in the paper (see section (2) for details). If new citing authors had different research practices that resulted in different citation patterns, then the entry of citing authors, who reported an affiliation in the paper, could potentially affect our findings. To test for this possibility, we restrict the sample of citing authors to those with a university position by 1914. The initial decline in the share of references quoting research from outside the camp was similar to the decline in the full sample; the recovery during the mid-1920s, however, was stronger (Figure 7, panel (a)).

For the results reported in Figure (7a), we investigate citations of established scientists and consider references to any research, independently of whether the research was produced by established scientists or by other scientists. If other scientists worked on different topics and entered the sample at differential rates across camps, the changes in citation patterns could be driven by the changing composition of research produced at home or abroad. We test for this possibility by investigating changes in citation shares of established scientists and by considering only references to research by other established scientists. The relative decline of references to research from *outside* the camp was similar to that of the full sample, but there was full recovery in these citation shares toward the end of the sample period (Figure 7, panel (b)). The relative decline of references to research from foreign authors *inside* the camp was smaller for this sample, and exhibited a stronger pre-trend. Different from the citation patterns reported for the full sample of scientists (Figure 5), established scientists went back to their pre-war citation behavior. This suggests that researchers who entered science during the war and the boycott were permanently less international than the established scientists.

Finally, we investigate how changes in the number of papers that were produced in each camp affected the citation patterns. For this test, we normalize the citation shares by the total number of potentially citeable papers produced in each camp. I.e. we divide the share of references to research from home by the number of potentially citeable papers produced at home. Similarly, we normalize the shares to research from foreign authors inside the camp and outside the camp.[19] The normalized share of references that quote research from outside the camp fell after 1914, particularly during the early boycott years (Figure 7, panel (c)). By the mid-1920s, the normalized shares fully recovered. The normalized share of references that quote research from foreign authors inside the camp also fell, but less sharply than the outside-camp share. In any given year, scientists in small countries did not publish many papers in one of the 161 top journals. As a result, the normalized share of citations to research from home (the excluded category in the regression) fluctuated substantially for the smaller countries, leading to relatively large variability of the results plotted in Figure 7,

[19]We compute the normalized share of citations to research produced at home as: $(\frac{c_{Home}}{C_{Total}} \times \frac{1}{N_{Home}})$, where N_{Home} is the number of potentially citeable papers produced at home in the five years preceding the publication of the citing paper. Similarly, we compute the normalized shares $(\frac{c_{Foreign-IN}}{C_{Total}} \times \frac{1}{N_{Foreign-IN}})$ and $(\frac{c_{Foreign-OUT}}{C_{Total}} \times \frac{1}{N_{Foreign-OUT}})$. The normalized shares can be interpreted as the probability that a reference cites a randomly selected paper produced in a certain camp. As we divide the citation shares by thousands of potentially citeable papers, the measure has a lower scale than before.

panel (c). We therefore re-estimate the regressions with the normalized citation shares for the six countries with the highest scientific output in our data. The results are indeed less volatile and confirm the previous findings (Figure 7, panel (d)).[20]

3.3 Changes in Supply of Knowledge or Demand for Knowledge?

The observed changes in citations could either be driven by a reduction in the supply of foreign knowledge or by a reduction in the demand for foreign knowledge, i.e. scientists knowing about foreign research but deciding not to quote it. If scientists decided not to quote research from the enemy camp despite knowing it, they would presumably also stop quoting research that was published before the war. We investigate a potential reduction in demand by estimating the equivalent of equations (1) and (2) for a pre-war (1900-1905) cohort of research.[21]

The evolution of citation shares to this pre-war cohort of research (Figure 8) looks different than the previous graphs. The share of references quoting research from *outside* the camp increased over time, relative to the share of references quoting research from home (the excluded category). Because of this convergence, the coefficient on the interaction of citations quoting research from outside the camp and the post-1914 indicator has the opposite sign than for the baseline results (Table 6, column 1). To control for the fact that foreign knowledge took time to reach the other camp, even in normal times, we include linear camp-specific trends in the regression. In this specification, the coefficient turns slightly negative, but not significantly so (Table 6, column 2). Any dip in references to research from outside the camp during the war and the boycott was much smaller than in the baseline results. The share of references to research from foreign authors *inside* the camp also increased over time and did not feature a strong dip during the war and the boycott. These results suggest that the reductions in the share of references quoting recent foreign research were predominately driven by a fall in supply of foreign knowledge, rather than by a fall in demand.

3.4 The Effect of WWI and the Boycott on Relative Citations of Neutrals

Our data also allow us to investigate the effect of WWI and the boycott on citation patterns of Neutrals by estimating equations (1) and (2) for Neutral papers. For them, foreign inside camp research was produced in other Neutral countries and foreign outside camp research was produced outside the Neutral camp.

[20] In further robustness checks, we show that the results also hold when we restrict the sample to citing papers of authors from small scientific countries and when we separate citation shares to research from outside the camp into the shares to research from enemy countries, neutral countries, and other countries (Appendix Figure A.5)

[21] These results fix the cohort of research (1900 to 1905) and investigate how citation shares to that cohort changed over time. In contrast, the main citation results investigate citation shares to a moving window of references, i.e. references to research published between 1901 and 1905 for citing papers published in 1905, but to research published between 1902 and 1906 for citing papers published in 1906, and so on.

Not surprisingly, the share of references to research from outside the camp was always very high because none of the Neutral countries was very large, and hence they relied on knowledge from the leading scientific nations. After 1914, there was only a small, but not significant, decline of the share of references to research from outside the camp. There was no decline of the share of references to foreign research from inside the camp (Figure 9, panel (a) and Appendix Table A.6 columns (1) and (2)).

The share of references to research from outside the camp can be divided into the share of references quoting Allied, Central, and other research. During the war and the boycott, Neutral papers increased the share of references that quote Allied research and decreased the share of references that quote Central research (Figure 9, panel (b) and Appendix Table A.6 columns (3) and (4)). These results are consistent with historical anecdotes that Neutral authors could still attend Allied conferences and that Germany restricted the delivery of scientific journals even to Neutral countries during WWI (Reinbothe, 2006, pp. 116).

4 Interruption of International Knowledge Flows and Scientific Productivity

4.1 Publications in Top Science Journals

Next, we investigate how the interruption of international knowledge flows impacted scientific productivity. To avoid selection bias caused by scientists of different quality entering or exiting the sample, we focus on all scientists who had a university position by 1914. The data contain 8,734 scientists with yearly productivity information for the years 1905 to 1930, which results in 227,084 person-year observations (Table 7). We then compare how changes in productivity of these scientists depended on their reliance on frontier knowledge from home or abroad.

To measure how much scientists depended on frontier knowledge from the home country, foreign countries inside the camp, or foreign countries outside the camp, we calculate how much scientists in the same field-country pair depended on research from each camp in the pre-war period. We measure the dependence on home or foreign knowledge by the share of pre-war references that quote frontier knowledge from home, foreign countries inside the camp, and foreign countries outside the camp. We also calculate the share of pre-war references that quote non-frontier knowledge from the three camps.

In Figure 10, panel (a), we show how certain field-country pairs (e.g. chemistry in the United States) depended on frontier knowledge from home or abroad in the pre-war period. In Panel (b) we divide frontier-knowledge dependence from abroad into its two components, dependence on frontier knowledge from foreign countries inside the camp and outside the camp.[22] A useful example of

[22]To simplify the exposition, we focus on frontier knowledge. For the regressions, we calculate the pre-war share

the identifying variation is the dependence on frontier knowledge of biology and biochemistry in the United States. For U.S. scientists, knowledge from outside the camp came predominantly from Germany. In the early 20th century, Germans led the world in biochemistry research. The very term "biochemistry," for example, was coined by Carl Neuberg in 1903. German biology, however, was less prominent. For U.S. scientists, knowledge from foreign countries inside the camp came predominantly from Britain. British biology contributed many important discoveries, but biochemistry was less developed. At home, U.S. biology had already joined the leading scientific countries, but biochemistry was yet to take off. In biology, 67 percent of pre-war references of U.S. scientists quoted frontier research from home, 27 percent quoted frontier research from foreign authors inside the camp, and only 6 percent quoted frontier research from outside the camp. In biochemistry, however, 56 percent of pre-war references quoted frontier research from home, 12 percent quoted frontier research from foreign authors inside the camp, and 32 percent quoted frontier research from outside the camp.

We estimate the effect of frontier knowledge by comparing productivity changes of Allied and Central scientists in country-field pairs that relied on frontier knowledge from foreign countries outside the camp and inside the camp, to productivity changes of scientists who relied on frontier knowledge from home:[23]

$$\begin{aligned} Publications_{ift} &= \beta_1 \cdot (\text{Reliance on Frontier OUT})_f \times 1\,[t = \text{Post 1914}] \\ &+ \beta_2 \cdot (\text{Reliance on Frontier IN})_f \times 1\,[t = \text{Post 1914}] \\ &+ \text{Scientist}FE_{if} + \text{Year}FE_t + X_{ift}\theta + \epsilon_{ift}. \end{aligned} \tag{3}$$

As the excluded category is the reliance on frontier knowledge from home, β_1 and β_2 measure productivity changes relative to scientists in field-country pairs that relied on frontier knowledge from home. The dependent variable measures the number of publications per year for each scientist. To ensure comparability across fields, we standardize yearly publications to mean zero and variance one within fields. The regression includes a full set of scientist fixed effects that control for permanent differences in quality across scientists. The regression also includes a full set of year fixed effects that control for yearly changes in productivity that affected all scientists in the same way, such as a reduction in productivity during the war years. We also control for the reliance on non-frontier knowledge from home, foreign countries inside the camp, and outside the camp, interacted with post-1914 indicators. Furthermore, we control for five-year career-age indicators interacted with the main field of each scientist, i.e. we control for different career-age productivity profiles for

of references quoting frontier research from home, non-frontier research from home, frontier research from foreign authors inside the camp, non-frontier research from inside the camp, frontier research from outside the camp, and non-frontier research from outside the camp.

[23]For scientists who worked in multiple fields, e.g. physical chemistry and chemistry, we assign the reliance on frontier and non-frontier knowledge from the different camps according to the share of their publications in each field.

physicists, chemists, and so on. We estimate this regression for different definitions of the research frontier (top 1%, top 3%, or top 5%). Standard errors are clustered at the country-times-field level.[24]

Scientists in field-country pairs that relied on top 1% knowledge from *outside* the camp published significantly less after 1914, compared to scientists who relied on top 1% knowledge from home (Table 8, column 1, significant at the 1 percent level). The estimated effect implies that scientists in a field-country pair heavily reliant on frontier knowledge from outside the camp, such as biochemistry in the United States, published 0.1 of a standard deviation fewer papers per year after 1914 (i.e. 0.15 fewer biochemistry papers per year, a reduction of 33 percent), compared to scientists in U.S. biology who relied mostly on frontier knowledge from home. Physics in Italy had one of the highest dependencies on frontier knowledge from outside the camp. Compared to a field-country pair that relied only on frontier knowledge from home, the estimated coefficient implies that Italian physicists published 0.27 of a standard deviation fewer papers per year after 1914 (i.e. 0.28 fewer physics papers per year, a reduction of 55 percent). Scientists in field-country pairs that relied on top 1% knowledge from *inside* the camp also published less after 1914, but not significantly so (Table 8, column 1).

To understand the timing of these effects, we estimate yearly coefficients as follows:

$$\begin{aligned} Publications_{ift} &= \sum_{\tau=1905(\tau\neq1913)}^{1930} \beta_{1\tau} \cdot (\text{Reliance on Frontier OUT})_f \times 1\left[t=\tau\right] \\ &+ \sum_{\tau=1905(\tau\neq1913)}^{1930} \beta_{2\tau} \cdot (\text{Reliance on Frontier IN})_f \times 1\left[t=\tau\right] \\ &+ \text{Scientist}FE_{if} + \text{Year}FE_t + X_{ift}\theta + \epsilon_{ift}. \end{aligned} \tag{4}$$

Scientists in field-country pairs that relied on frontier knowledge (as measured by the top 1%) from outside the camp, suffered a sharp decline in productivity after 1914, compared to scientists who relied on frontier knowledge from home (Figure 11). For these scientists, relative productivity did not recover. Scientists in field-country pairs that relied on frontier knowledge from inside the camp, suffered a smaller decline in productivity after 1914, which was not persistent.

If we alternatively measure the research frontier with top 3% research, we estimate a smaller, but still highly significant, productivity decline for scientists who relied on frontier knowledge from *outside* the camp, compared to scientists who relied on frontier knowledge from home. If we measure the frontier with top 5% research, we estimate an even smaller, but still significant, decline in productivity (Table 8, columns 2 and 3, significant at the 1 percent and 10 percent level, respectively). Scientists who relied on frontier knowledge from foreign countries *inside* the camp suffered smaller and insignificant productivity declines. Figure 12 shows the yearly reduction in productivity for different definitions of the research frontier, focusing on the effect of losing access to frontier knowledge from outside the camp. Access to the knowledge frontier matters, and in particular access

[24]We assign each scientist to his main research field according to his publications in each field.

to the very best research, as measured by the top 1%.

Robustness

For the previous results, we normalize the dependent variable by the number of authors per paper. Without this normalization, the results are very similar (Table 9, column 1). The results are also similar if we exclude chemists, whose scientific productivity may have been affected by research on chemical weapons (Table 9, column 2). We also show that results remain similar, if we control for field-times-post-1914 indicators (Table 9, column 3). This allows for a differential development of each field, e.g. chemistry or physics, after 1914. In a further specification, we control for camp-times-post-1914 indicators. While the point estimates are slightly smaller, they remain significant at the 10 percent level when we measure the frontier with top 1% research (Table 9, column 4). The results also remain similar if we control for both field-times-post-1914 and camp-times-post-1914 indicators (Table 9, column 5). It may have been the case that scientists in field-country pairs heavily reliant on frontier knowledge from outside the camp published relatively more of their papers in journals from the other camp. Thus, in addition to contending with reduced international knowledge flows, these scientists may have faced greater difficulty in publishing in foreign journals. As a consequence, scientists who relied on frontier knowledge from outside the camp may have published fewer papers. We explore this concern by focusing on publications in own-camp journals. The results remain unchanged (Table 9, column 6), presumably because the majority of scientists published in journals edited in their own camp (see Appendix Table A.4).

Field-level Variation Within the United States

Finally, we explore the effect of losing access to frontier knowledge using variation across fields in the United States only. Some U.S. fields, such as biochemistry, relied on frontier knowledge from outside the camp, while others, such as biology, relied mostly on frontier knowledge from home.

In the pre-war period, the productivity of U.S. scientists in fields that relied on frontier knowledge from *outside* the camp improved relative to scientists in fields that relied on frontier knowledge from home (Figure 13). After 1914, the productivity of scientists in fields that relied on frontier knowledge from outside the camp declined sharply and did not recover until 1930. We test whether the trend break in 1914 was statistically significant with a regression model that adds linear trends and the interaction of each linear trend with a post-1914 indicator to regression (3). The estimated trend-break in 1914 for the "Reliance on Frontier *OUT*" has a p-value of 0.055.[25] The productivity

[25] More specifically, the regression includes linear trends for reliance on "Frontier *OUT*," "Frontier *IN*," and "Home," plus non-frontier trends and the interaction of each of these trends with a post-1914 indicator. We then test whether "Reliance on Frontier *OUT*" interacted with "post-1914" is significantly different from 0. The U.S. sample includes 11 fields and we cluster standard errors at the field level. To avoid a downward bias in estimated standard errors due to the small number of clusters (Cameron et al., 2008), we implement a cluster-bootstrap with asymptotic refinement as suggested by Cameron and Miller (2015).

of U.S. scientists in fields that relied on frontier knowledge from foreign countries *inside* the camp also improved in the pre-war period. While the productivity of scientists in these fields continued to improve after 1914, it improved at a somewhat lower pace. The trend-break in 1914 for the "Reliance on Frontier *IN*" was smaller than for scientists in fields that relied on frontier knowledge from outside the camp (p-value of 0.099).

4.2 Nobel-Nominated Research

Nobel-Nominated Papers

The previous results indicate that scientists in field-country pairs that relied more on frontier knowledge from abroad, published significantly fewer papers in top journals after 1914. To further investigate how the interruption of knowledge flows affected the quality of research, we analyze changes in the probability of producing a paper that was nominated for a Nobel Prize.[26] The Nobel Prize was awarded by the Academy of Sciences and the Karolinska Institutet in Sweden, a *Neutral* country.

We collect data on all nominations for the physics, chemistry, and physiology/medicine Nobel Prizes from the Nobel Nomination Archive (see Nobelprize.org, 2014). Between 1905 and 1945, 993 individuals were nominated for a Nobel Prize at least once, 131 of them eventually won it. The database does not list the exact research that led to a nomination. We define that research by searching our publication data for the highest cited paper (counting citations until today) that a nominee published before his last nomination (see Appendix B.3 for details). We then generate an indicator 'Nobel-nominated paper' that equals one if a scientist published his Nobel-nominated paper in a certain year, and zero for all other years.

Arthur Compton, for example, received the 1927 Nobel Prize in physics for the discovery of the effect named after him. He was last nominated for the prize in 1927 and we therefore search for the highest cited paper that he published before 1927. His article "A quantum theory of the scattering of x-rays by light elements" was published in the *Physical Review* in 1923, and received (until today) 355 citations, more than any other of his pre-1927 papers. For Arthur Compton the 'Nobel-nominated paper' indicator therefore equals one in 1923, and zero in all other years.[27] Using the 'Nobel-nominated paper' indicator as the dependent variable, we estimate the following regression for our sample of university scientists:[28]

[26]The usual citation-based measures of research quality would be uninformative in this context, because citations were heavily distorted during the war and the boycott (see section 3).

[27]Our measure of Nobel-nominated research identifies a single year. Jones and Weinberg (2011) have collected biographical data to identify the period of key research that led to a Nobel Prize. For Nobel Prize winners, our measure has a correlation of 0.69 with the middle year of the period of key research reported by Jones and Weinberg. The detailed biographical information that Jones and Weinberg use to construct their measure is not available for scientists who were nominated for the prize but did not win.

[28]The estimation includes 234 nominees, among them 42 winners. Of the 993 potential nominees, 474 published their Nobel-nominated paper between 1905 and 1930, and 234 of them had a university position by 1914.

$$
\begin{aligned}
Nobel-Nominated\ Paper_{ift} &= \beta_1 \cdot (\text{Reliance on Frontier OUT})_f \times 1\,[t = \text{Post 1914}] \\
&+ \beta_2 \cdot (\text{Reliance on Frontier IN})_f \times 1\,[t = \text{Post 1914}] \qquad (5) \\
&+ \text{Scientist}FE_{if} + \text{Year}FE_t + X_{ift}\theta + \epsilon_{ift}.
\end{aligned}
$$

After 1914, the probability of publishing a Nobel-nominated paper declined significantly for scientists in field-country pairs that relied on frontier knowledge from *outside* the camp (Table 10, column 1, significant at the 5 percent level). The estimated effect indicates that the probability of publishing a Nobel-nominated paper declined by 0.001 for scientists in a field like U.S. biochemistry that relied heavily on frontier knowledge from outside the camp, compared to scientists in a field like U.S. biology that relied mostly on frontier knowledge from home. The pre-war period probability of writing a Nobel-nominated paper in fields that relied on frontier knowledge from abroad is also 0.001. Thus, the results indicate that losing access to frontier knowledge from outside the camp effectively wiped out the chance of writing a paper worthy of a Nobel Prize nomination.

Using less-stringent definitions of the research frontier, we estimate reductions in the probability of writing a Nobel-nominated paper that are significant but about half as large, in absolute magnitude (Table 10, columns 3 and 5, significant at the 1 percent and 5 percent level). These results further highlight the importance of access to the very best research for producing path-breaking ideas.

Weighing Nobel-Nominated Papers by the Number of Nominations

While some candidates "only" received one nomination for the Nobel Prize, others received many. To distinguish the quality of papers at the very highest level of the quality spectrum, we construct a second measure that weighs the Nobel-nominated papers by the number of nominations. Because scientists who eventually won the prize experienced a hike in nominations in the last two years before winning (see Appendix Figure A.6), we focus on the number of nominations during the last two years before a candidate's last nomination. The physicists with the highest number of nominations in the last two years were Albert Einstein (31 nominations), Jean Perrin (18), Werner Heisenberg (17), and Erwin Schrödinger (17); they all eventually won the Nobel Prize, and they are considered to have made some of the most outstanding contributions to physics in this period.

The measure is highly predictive of winning the Nobel Prize.[29] Candidates with one nomination only had a 4 percent chance of winning. Candidates with two nominations had a 13 percent chance, candidates with three nominations had a 16 percent chance, candidates with four nominations had a 19 percent chance, candidates with five to nine nominations had a 40 percent chance, and candidates

[29]The number of nominations *in the last two years* before the last nomination is a better predictor of winning than the total number of nominations because the total number of nominations is censored for winners (i.e. most of them were no longer nominated after winning).

with more than nine nominations had a 61 percent chance of winning (Figure 14).

After 1914, scientists in field-country pairs that relied on frontier knowledge from outside the camp published fewer papers that received a high number of nominations for the Nobel Prize (Table 10, column 2, significant at the 1 percent level). Using the less stringent definitions of the research frontier we find smaller, but still significant, reductions (Table 10, columns 4 and 6, significant at the 5 percent level). Losing access to the very best research, as measured by the top 1%, was particularly detrimental for producing revolutionary research.

Robustness

The results on (nomination weighted) Nobel-nominated papers are robust to excluding chemists (Table 11, columns 1 and 2). They are also robust to controlling for field-times-post-1914 indicators that allow for a differential evolution of Nobel-nominated papers in different fields, e.g. physical chemistry versus biochemistry, after 1914 (Table 11, columns 3 and 4). The results are also robust to controlling for camp-times-post-1914 indicators that allow for a differential evolution of different camps after 1914, e.g. the Allied camp improving in quality (Table 11, columns 5 and 6). Finally, the results are robust to controlling for both field and camp-times-post-1914 indicators (Table 11, columns 7 and 8).

5 Conclusion

We show that WWI and the subsequent boycott against scientists from Central countries significantly reduced international knowledge flows, as measured by citations in academic papers. We also show that scientists in field-country pairs that relied on frontier knowledge from countries outside the camp published fewer papers after 1914, and produced less work that earned nominations for the Nobel Prize. Access to frontier knowledge produced at home, that is, to use Newton's terminology, "standing on ye shoulders of [*home*] Giants" sheltered scientists from the negative effects of reduced international knowledge flows.

The historical episode studied in this paper allows us to investigate a dramatic decline in worldwide international knowledge flows, which enables us to estimate the causal effect of frontier knowledge on scientific productivity. Moreover, by measuring citations to research for almost 100 years, we can distinguish the knowledge frontier from short-lived scientific fashions. Even though the costs of accessing frontier knowledge may have fallen since the early 20th century, especially with the introduction of the internet, distance still matters for the transmission of ideas. Frontier knowledge travels faster within scientific networks than across networks, partly because, even today, face-to-face interaction is a superior way of transmitting ideas (e.g. Glaeser, 2011 and Head et al., 2015). As a result, distance still limits access to the knowledge frontier and slows down scientific progress.

Our results suggest two broad policy measures to foster the progress of science. Because knowledge diffuses more easily within country-borders (e.g. Table 3 and also Jaffe et al., 1993; Thompson and Fox-Kean, 2005), creating an environment that facilitates the production of frontier knowledge at home will benefit scientific progress. Increasing the production of frontier knowledge depends crucially on the career choices of talented individuals. If the most talented individuals produce frontier knowledge instead of entering rent-seeking occupations, the potential benefits to society can be very large (Murphy et al., 1991). Learning the tools and approaches to produce frontier knowledge starts early in a budding scientist's career. High-quality PhD programs at universities where frontier research proliferates can therefore help to put young scientists on the most-promising career paths (Waldinger, 2010). Moreover, the institutional arrangement of the scientific enterprise should be geared towards the production of frontier knowledge. Funding, for example, should allow scientists to undertake high-risk but high-return projects (Azoulay et al., 2011).

The second set of policy measures to foster scientific progress should improve access to frontier knowledge produced in distant locations. The Danish physicist and Nobel Laureate Niels Bohr highlighted that being from a small country meant that one could not be self-sufficient for the development of new ideas.[30] He kept up to date with recent developments by frequently interacting with physicists from both camps, even during the boycott. One of the most famous examples is the series of lectures he held at Göttingen in 1922, sometimes dubbed the 'Bohr Festival.' At this event, Bohr not only explained his latest theories of atomic structure, but also exchanged ideas with his listeners, including the (future) Nobel Laureates James Franck, Max Born, Wolfgang Pauli, and the young physics prodigy Werner Heisenberg (e.g. Mehra and Rechenberg, 1982, pp. 345). As Bohr had worked with Ernest Rutherford in Manchester until 1916, he was also in constant contact with the physics community in Britain. Access to frontier research can be facilitated through short and long term visits at the centers of science and through the attendance of high quality conferences (de Leon and McQuillin, 2015). Furthermore, access to the highest-quality journals facilitates exposure to frontier knowledge. Open access policies, for example, may be a way to increase access to the knowledge frontier for individuals in remote scientific locations (e.g. Evans and Reimer, 2009; McCabe and Snyder, 2015).

[30]He acknowledged the importance of German and British research for his work and stated: "When one...knows a little about from how diverse quarters the germs for fruitful work stem, one is hardly likely to overestimate personal merit in the domain of science, but rather sees in every advance a fruit of the mutual support in the endeavors for the common goal" (Bohr, 2007, p. 172).

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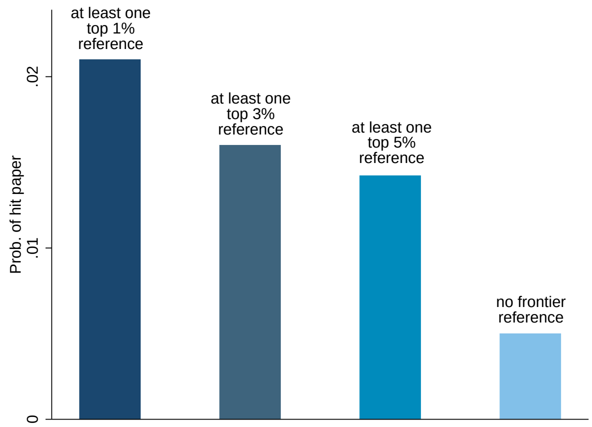
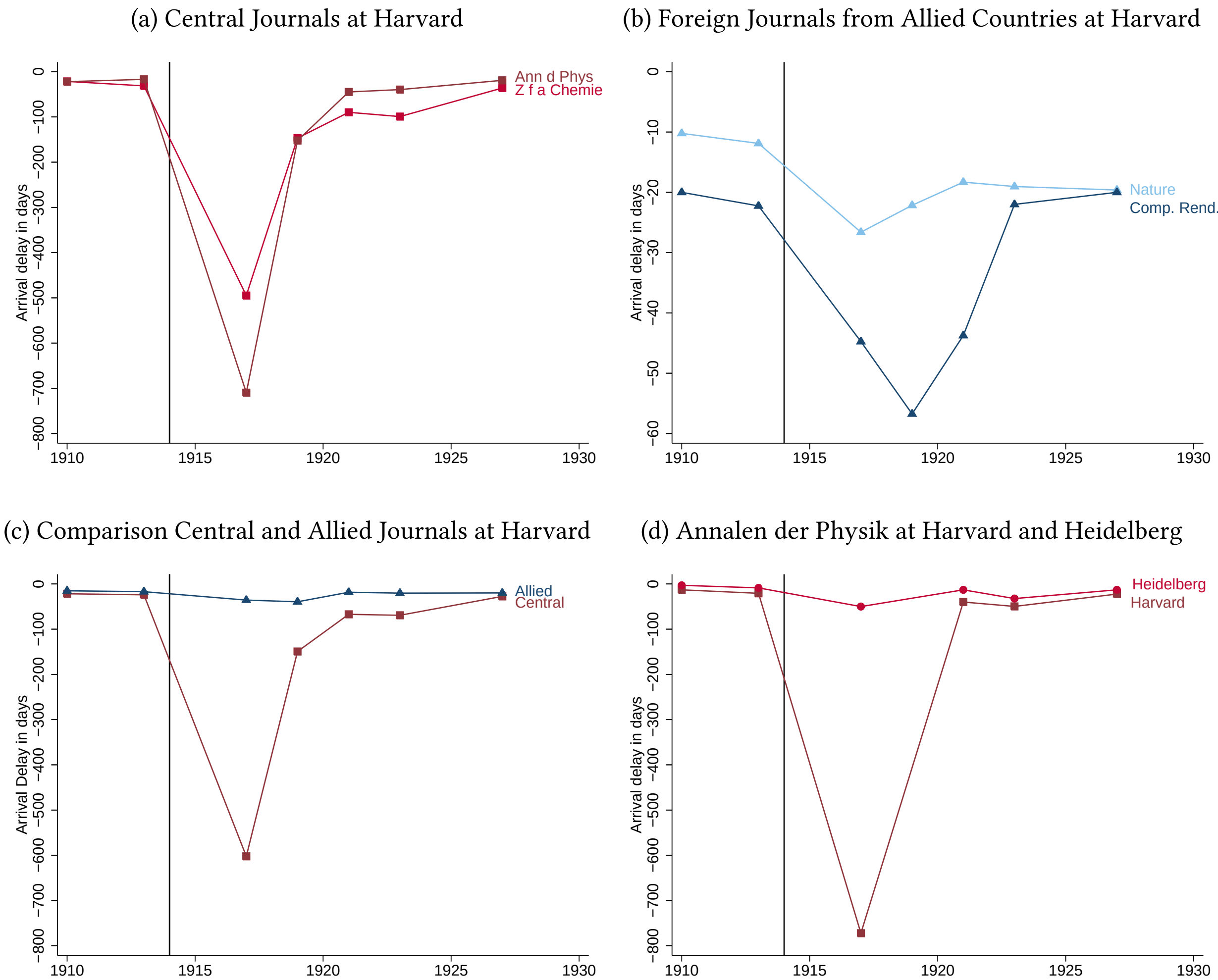
Figures

Figure 1:
Probability of Hit Paper Depending on the Quality of Cited References



Notes: The Figure plots the probability that a paper becomes a hit, i.e. ends up in the top 1 percent of the field-level citation distribution until today, depending on the quality of cited references. Only references to research published in the five years preceding the publication of the citing paper are considered. Self-citations are excluded. The bar "at least one top 1% reference" shows the probability that the citing paper becomes a hit if it cites at least one reference that ends up in the top 1% of the citation distribution until today. The bar "at least one top 3% reference" shows the probability that the citing paper becomes a hit if it cites at least one reference that ends up in the top 3% of the citation distribution, and so on. The bar "no frontier reference" shows the probability that the citing paper becomes a hit if it does not cite references that end up in the top 5% of the citation distribution. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 2:
Arrival Delay of Journals



Notes: Panel (a) plots the average delay between publication and arrival date at the Harvard library for the German journals *Zeitschrift für analytische Chemie* and *Annalen der Physik*. Arrival dates are based on library entry stamps (see Appendix Figure A.2 for an example). Delays are calculated as yearly averages for 1910, 1913, 1917, 1919, 1921, 1923, and 1927. Panel (b) plots the delay for two Allied journals, the British journal *Nature* and the French journal *Comptes Rendus*. Panel (c) compares delays for German journals and Allied journals. For this panel, we average the yearly delays for the two journals in each group. Panel (d) compares delays for the *Annalen der Physik* at Harvard and at the German University of Heidelberg. In Panel (d), the delay at Harvard is slightly different from that reported in panel (a) because we focus on the journal issues that were available at both Harvard and Heidelberg. Data on entry stamps were collected by the authors at Harvard and at the University of Heidelberg (see Appendix D for details).

Figure 3:
CENTRAL ATTENDANCE AT SOLVAY CONFERENCE

(a) 1911

(b) 1913

(c) 1921

(d) 1924

(e) 1927

(f) 1930

Notes: The Figure shows delegates at the *Solvay Conferences* in physics. Circles indicate delegates from Central countries. See Appendix Table A.2 for delegate names. Data were collected by the authors from Mehra (1975) (see Appendix F for details).

Figure 4: Example citing paper and references

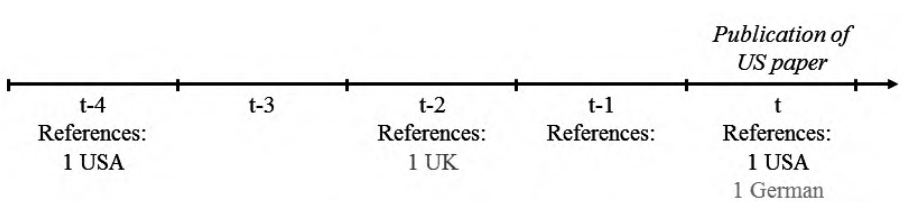
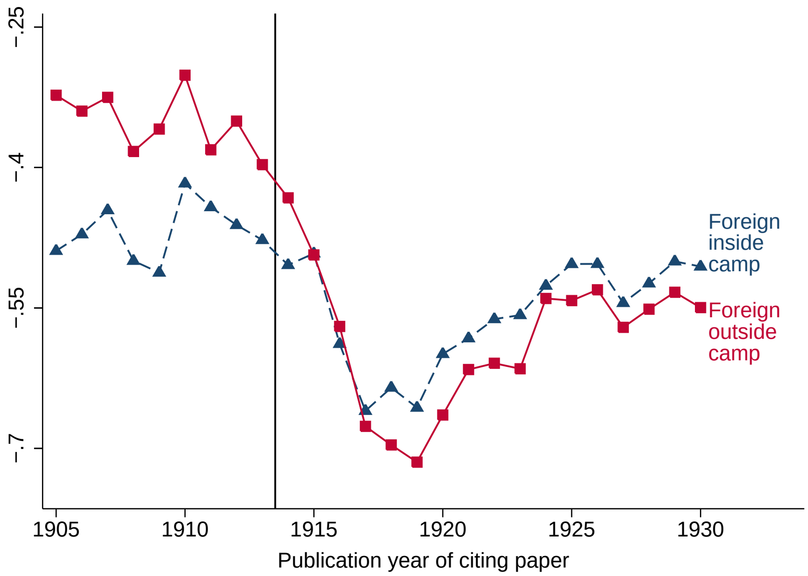


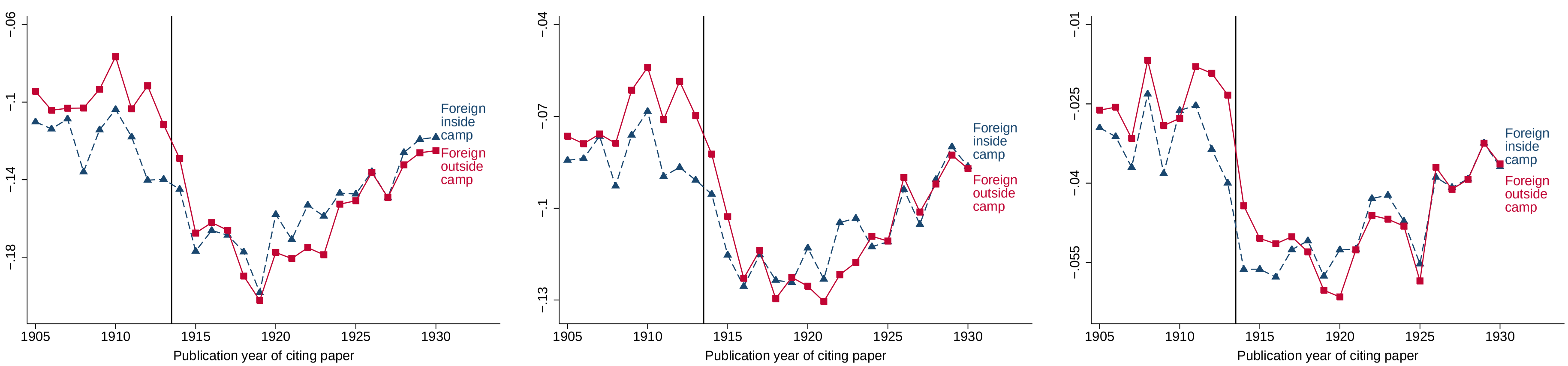
Figure 5:
CITATION SHARES RELATIVE TO HOME



Notes: The Figure plots parameter estimates of regression (2). The "Foreign outside camp" line reports point estimates (ω_τ) that measure the share of citations to research from outside the camp, relative to research from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure the share of citations to research from foreign authors inside the camp, relative to research from home. We focus on citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures the relative share of citations to research published between 1901 and 1905. The second dot (1906) measures the relative share of citations to research published between 1902 and 1906, and so on. Point estimates and corresponding standard errors are reported in Appendix Table A.5. All point estimates are significantly different from 0 at the 1 percent level. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 6:
CITATION SHARES RELATIVE TO HOME: CITATIONS TO HIGH QUALITY RESEARCH

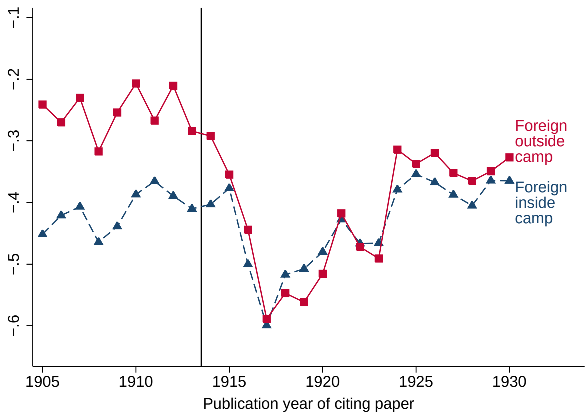
(a) Citations to Top 5% Research (b) Citations to Top 3% Research (c) Citations to Top 1% Research



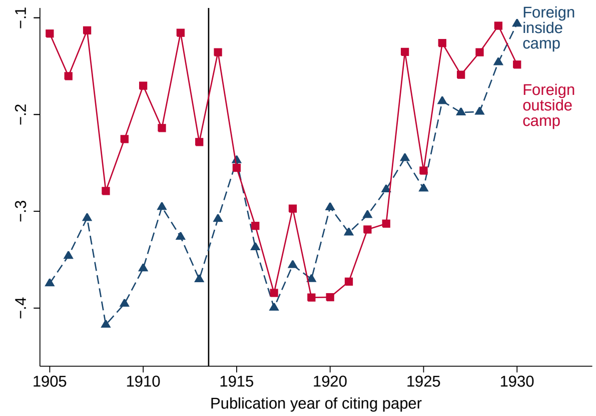
Notes: The Figures plot parameter estimates from three regressions equivalent to regression (2). For the results reported in panel (a), we split the share of references to research from home into references that ended up in the top 5% of the citation distribution and references that ended up in the bottom 95%. Similarly, we split the shares to research produced inside the camp and outside the camp. The "Foreign outside camp" line measures the share of citations to top 5% research from outside the camp, relative to top 5% research from home. The "Foreign inside camp" line measures the share of citations to top 5% research from foreign authors inside the camp, relative to top 5% research from home. The regressions also include the citation shares to non-frontier research from outside the camp, inside the camp, and home. In all panels, we focus on citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures the relative share of citations to top 5% research published between 1901 and 1905, and so on. Panel (b) reports estimates for changes in the share of references to research that ended up in the top 3% of the citation distribution, and panel (c) reports estimates for changes in the share of references to research that ended up in the top 1% of the citation distribution. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 7:
Citation Shares Relative to Home: Robustness Checks

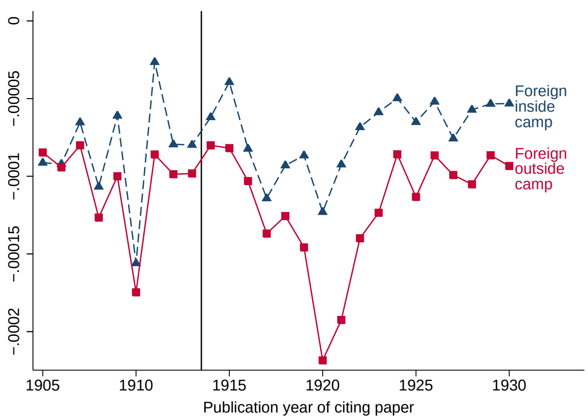
(a) Citing Authors with University Position by 1914



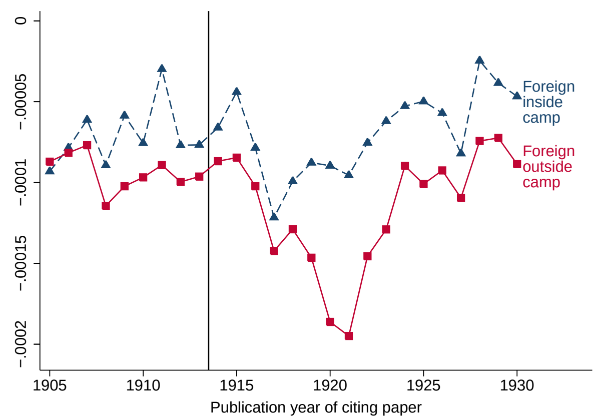
(b) Citing and Cited Authors with University Position by 1914



(c) Citing and Cited Authors with University Position by 1914 and Normalize Shares

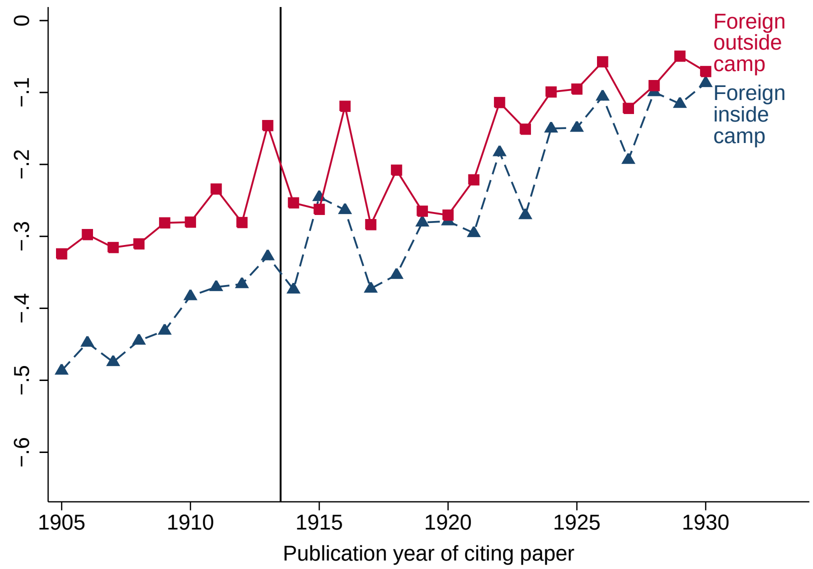


(d) Additionally Restrict Sample to Six Countries with Largest Scientific Output



Notes: The Figure in panel (a) plots parameter estimates of regression (2) for citing authors with a university position by 1914. The Figure in panel (b) plots parameter estimates for citing authors with a university position by 1914 and only considers citations to research published by authors with a university position by 1914. In addition to the previous restrictions, the Figure in panel (c) plots parameter estimates for a regression with normalized citation shares as the dependent variable. We normalize citation shares by the number of potentially citeable papers in each camp. The Figure in panel (d) plots parameter estimates where we further restrict the sample of citing and cited authors to those from the six largest scientific countries in our data (USA, Germany, UK, Canada, Austria, and Hungary). In all panels, the "Foreign outside camp" line reports point estimates that measure the share of citations to research from outside the camp, relative to research from home. The "Foreign inside camp" line reports point estimates that measure the share of citations to research from foreign authors inside the camp, relative to research from home. In all panels, we focus on citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures the relative share of citations to research published between 1901 and 1905, and so on. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 8:
CITATION SHARES RELATIVE TO HOME: CITATIONS TO 1900-1905 RESEARCH

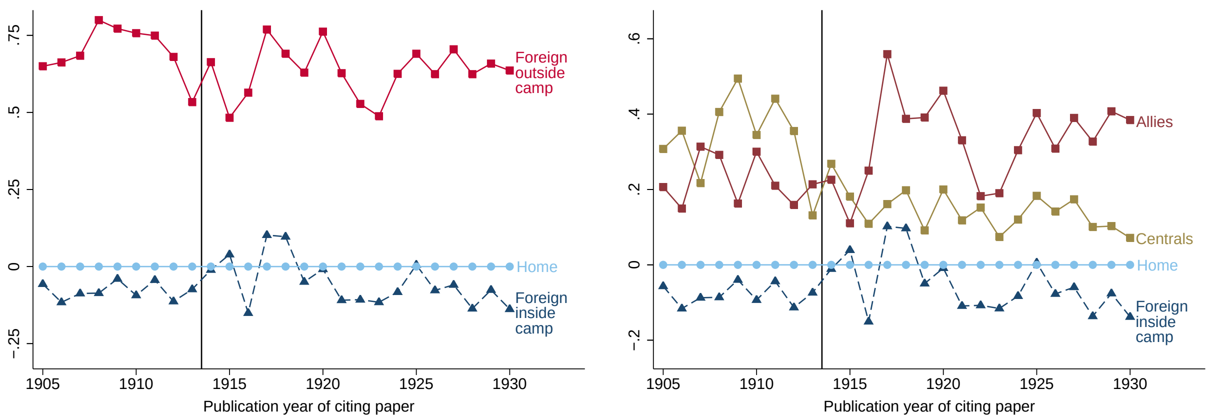


Notes: The Figure plots parameter estimates of a version of regression (2) with citation shares to 1900-1905 research as the dependent variable. The "Foreign outside camp" line reports point estimates (ω_τ) that measure the share of citations to 1900-1905 research from outside the camp, relative to 1900-1905 research from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure the share of citations to 1900-1905 research from foreign authors inside the camp, relative to 1900-1905 research from home. Unlike the previous results, each dot of the "Foreign outside camp" line measures the relative share of citations to 1900-1905 research. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 9:
CITATION SHARES RELATIVE TO HOME: NEUTRAL AUTHORS

(a) Relative Reliance on Foreign Work

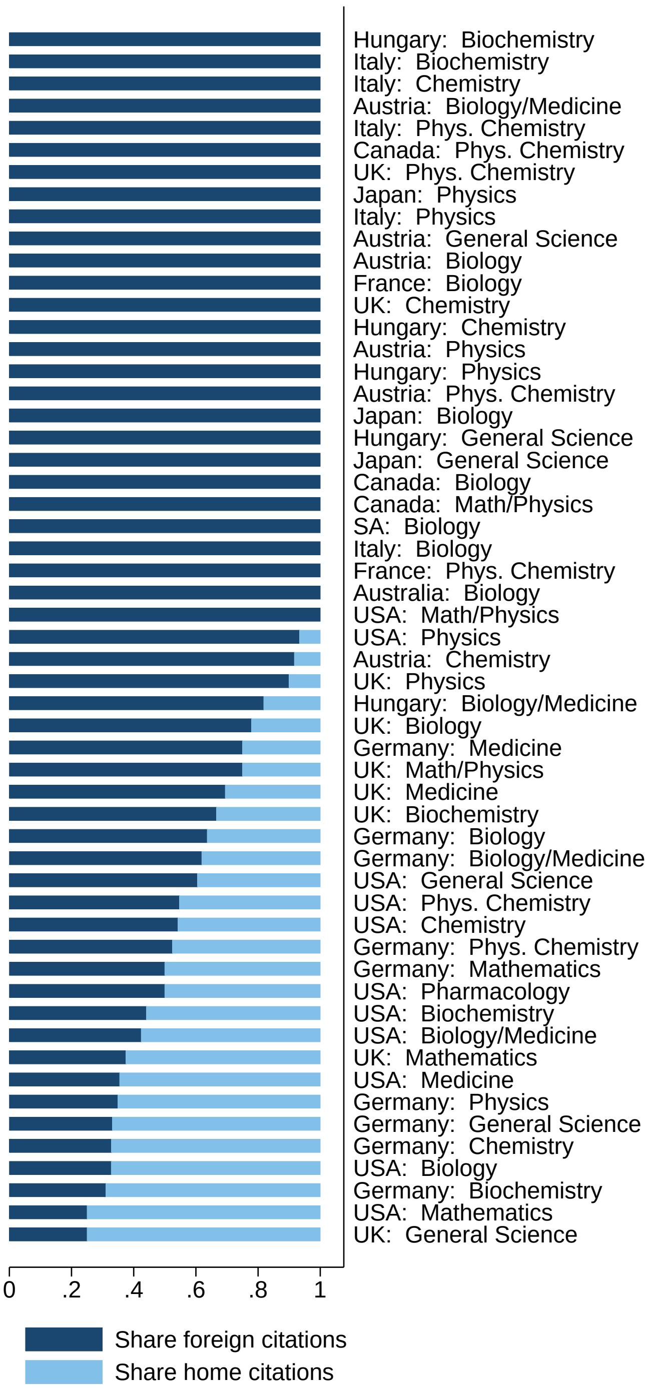
(b) Relative Reliance on Allied and Central Work



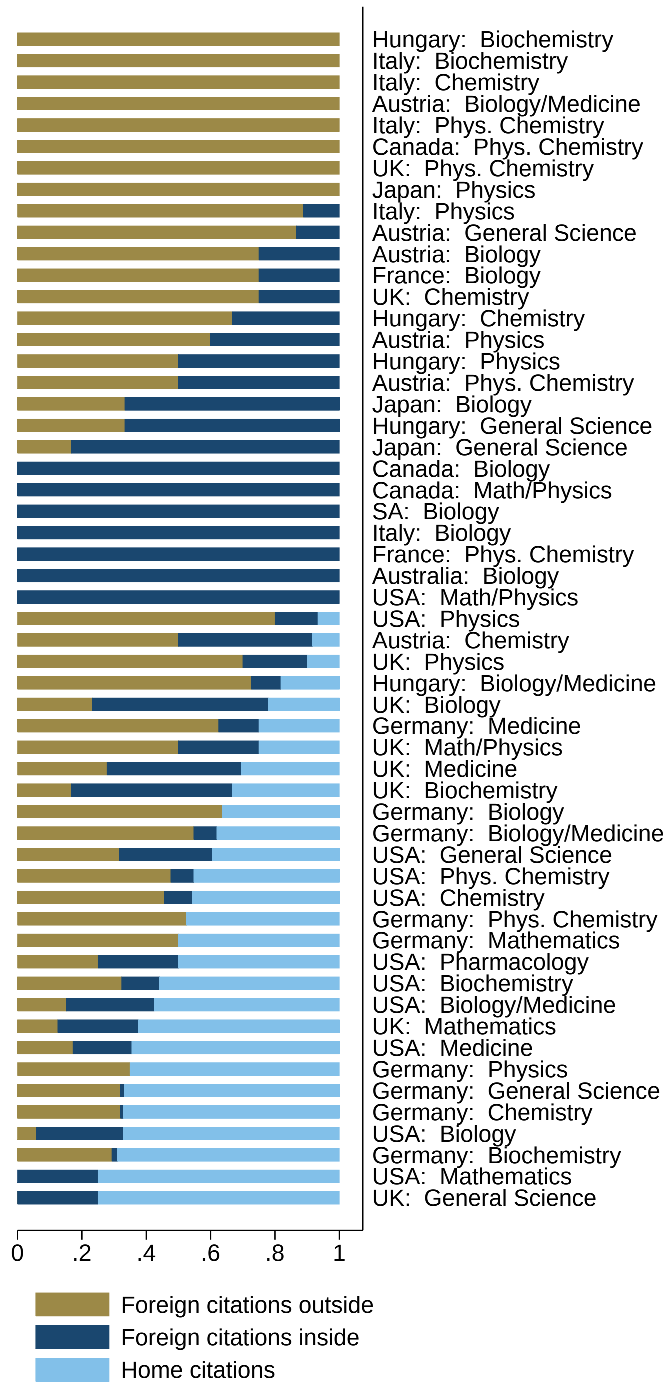
Notes: The Figure plots parameter estimates of two versions of regression (2) for Neutral citing papers. In panel (a), the "Foreign outside camp" line reports point estimates that measure the share of citations to research from outside the Neutral camp, relative to research from home. The "Foreign inside camp" line reports point estimates that measure the share of citations to research from foreign authors inside the Neutral camp, relative to research from home. In panel (b), the "Allies" line reports point estimates that measure the share of citations to Allied research, relative to research from home. The "Centrals" line reports point estimates that measure the share of citations to Central research, relative to research from home. The "Foreign inside camp" line reports point estimates that measure the share of citations to research from foreign authors inside the Neutral camp, relative to research from home. The regression also includes the share of citations to research by authors from other countries. In both panels, we focus on citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures the relative share of citations to research published between 1901 and 1905, and so on. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 10:
Pre-War Reliance on Frontier Knowledge

(a) Citations to Research from Abroad and Home

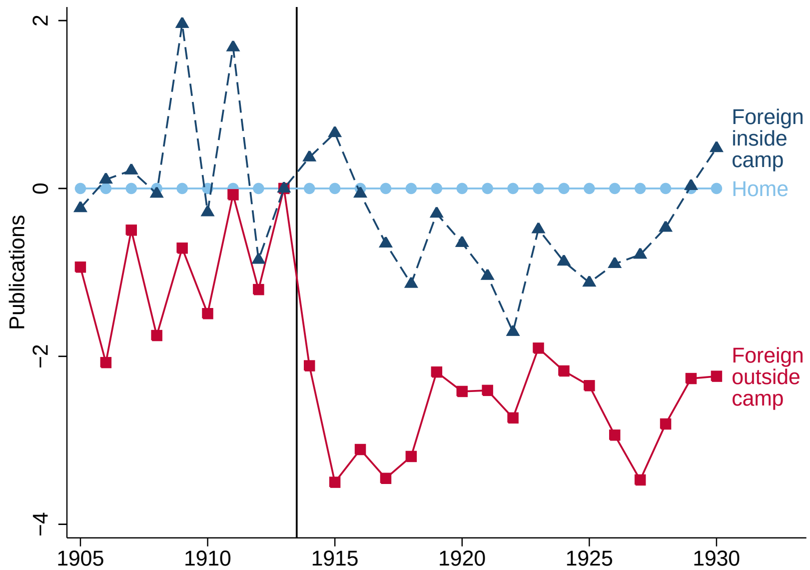


(b) Citations to Research from Inside the Camp, Outside the Camp, and Home



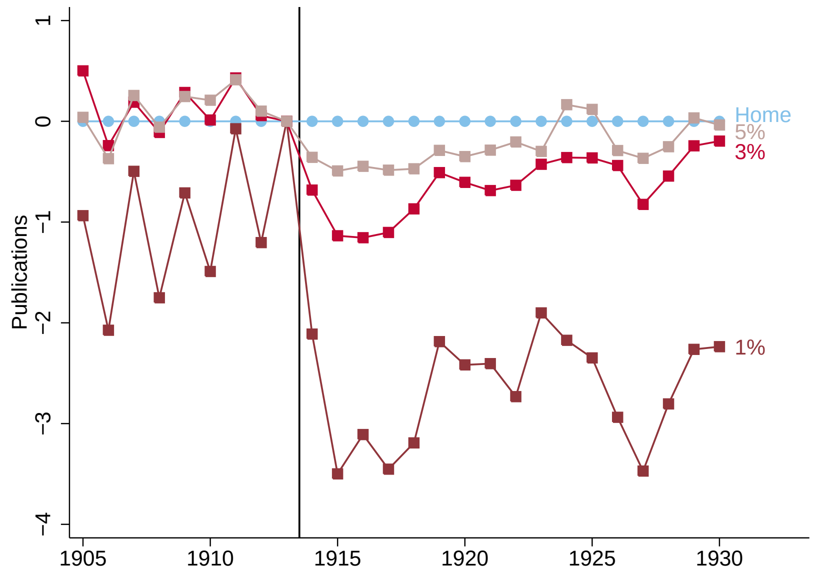
Notes: Panel (a) shows the pre-war reliance on frontier (top 3%) knowledge from home or abroad for each country-field pair. Pre-war reliance on frontier knowledge is calculated as the average share of citations to recent research produced at home or abroad for all citing papers published by all university scientists in each country-field pair between 1900 to 1913. Panel (b) further differentiates citations to foreign research into citations to research from outside the camp and inside the camp. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 11:
Dependence on Frontier Knowledge (1%) and Productivity: Publications



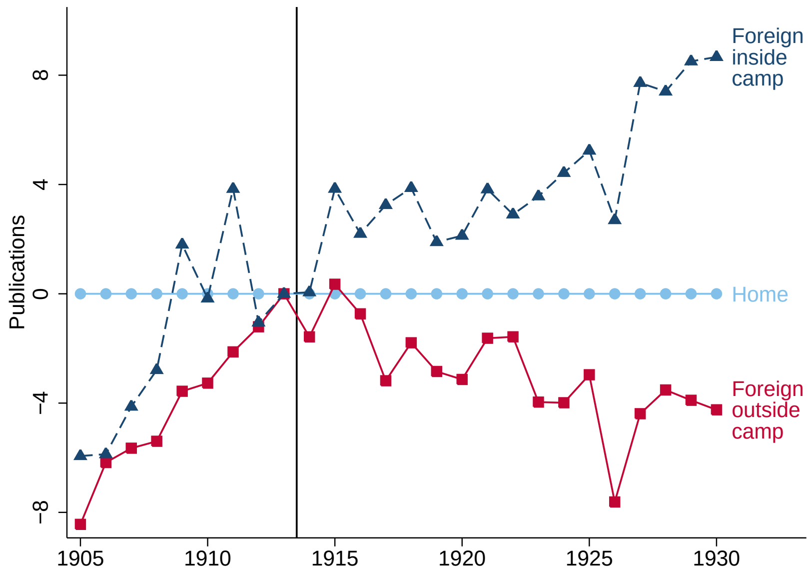
Notes: The Figure plots parameter estimates from regression (4). The "Foreign outside camp" line reports point estimates ($\beta_{1\tau}$) that measure changes in yearly publications for scientists in field-country pairs that relied on pre-1914 frontier knowledge from outside the camp, compared to scientists who relied on pre-1914 frontier knowledge from home. The "Foreign inside camp" line reports point estimates ($\beta_{2\tau}$) that measure changes in yearly publications for scientists in field-country pairs that relied on pre-1914 frontier knowledge from foreign authors inside the camp, compared to scientists who relied on pre-1914 frontier knowledge from home. Reliance on pre-1914 frontier knowledge is measured by pre-1914 citations to frontier research at the field-country pair level. Frontier knowledge is defined as research that ended up in the top 1% of the subject-level citation distribution until today. The regression also controls for reliance on non-frontier knowledge from each camp interacted with year indicators. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 12:
Dependence on Frontier Knowledge and Productivity: Different Frontiers



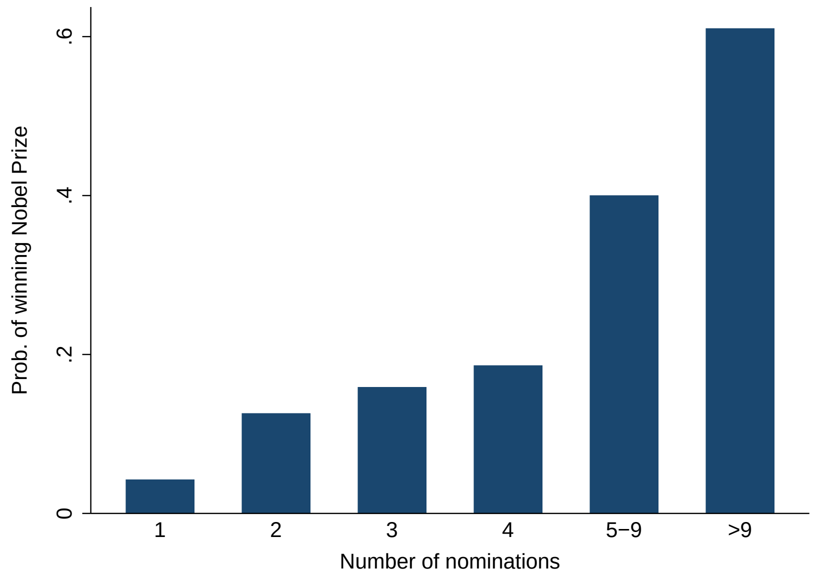
Notes: The Figure plots parameter estimates from three versions of regression (4), each for a different definition of frontier knowledge. The "1%" line reports point estimates that measure relative yearly publications for scientists in fields that relied on pre-1914 frontier knowledge from outside the camp, when frontier knowledge is defined as research that ended up in the top 1% of the subject-level citation distribution until today. Similarly, the "3%" ("5%") line reports point estimates when frontier knowledge is defined as research that ended up in the top 3% (5%) of the subject-level citation distribution until today. Each of the three regressions also controls for reliance on frontier knowledge from inside the camp interacted with year indicators, and dependence on non-frontier knowledge from each camp interacted with year indicators. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 13:
Dependence on Frontier Knowledge (1%) and Productivity: Within U.S. Variation



Notes: The Figure plots parameter estimates from regression (4) when we restrict the sample to scientists based in the United States. The "Foreign outside camp" line reports point estimates ($\beta_{1\tau}$) that measure changes in yearly publications for scientists in field-country pairs that relied on pre-1914 frontier knowledge from outside the camp, compared to scientists who relied on pre-1914 frontier knowledge from home. The "Foreign inside camp" line reports point estimates ($\beta_{2\tau}$) that measure changes in yearly publications for scientists in field-country pairs that relied on pre-1914 frontier knowledge from foreign authors inside the camp, compared to scientists who relied on pre-1914 frontier knowledge from home. Reliance on pre-1914 frontier knowledge is measured by pre-1914 citations to frontier research at the field-country pair level. Frontier knowledge is defined as research that ended up in the top 1% of the subject-level citation distribution until today. The regression also controls for dependence on non-frontier knowledge from each camp interacted with year indicators. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure 14:
Probability of Winning Nobel Prize Depending on Number of Nominations



Notes: The Figure plots the probability of winning the Nobel Prize depending on the number of nominations. The number of nominations is the sum of nominations in year t and year $t-1$ if year t is a candidate's last nomination in the interval 1905 to 1945. Data were collected by the authors from Nobelprize.org (2014) and include 991 candidates for the Nobel Prize and 131 winners. The data contain 589 candidates with one nomination, 159 with two nominations, 63 with three nominations, 43 with four nominations, 80 with five to nine nominations, and 59 with more than nine nominations.

Tables

Table 1:
SCIENTIFIC CAMPS DURING THE BOYCOTT

Allies	Centrals	Neutrals
U.S.A.	Germany	Switzerland
U.K. (incl. Ireland)	Austria	Netherlands
France	Hungary	Sweden
Canada	Bulgaria	Denmark
Japan	Ottoman E. / Turkey	Norway
Italy		Czechoslovakia
Belgium		Finland
Australia		Spain
Rumania		Monaco
Poland		
Brazil		
South Africa		
Greece		
New Zealand		
Portugal		
Serbia		

Notes: The Table reports the countries in each camp during WWI and the boycott. Countries are ordered by scientific output in our data. Countries are classified following the definition of the International Research Council (IRC). Austria-Hungary was split into two countries after WWI. Turkey emerged from parts of the Ottoman Empire after WWI.

Table 2:
Attendance to International Congresses of Mathematicians

Year	*Location*	*Delegates from:*							
		Germany	*Switzerland*	*France*	*U.S.A.*	*Canada*	*U.K.*	*Italy*	*Others*
1897	Zurich	53	68	29	7	0	3	25	57
1900	Paris	26	7	93	19	1	12	23	69
1904	Heidelberg	204	13	29	19	1	8	14	108
1908	Rome	174	18	92	27	1	33	213	142
1912	Cambridge (U.K.)	70	10	45	87	5	270	41	181
1916	Stockholm				*Canceled*				
1920	Strasbourg	0	12	112	15	1	11	7	99
1924	Toronto	0	5	45	270	118	93	15	80
1928	Bologna	106	48	91	76	7	64	412	312
1932	Zurich	142	185	89	102	2	49	81	203

Notes: The Table reports the number of delegates at each *International Congress of Mathematicians* by country. Data were collected by the authors from *Proceedings of the International Congresses of Mathematicians* (see Appendix E for details).

Table 3:
Summary Statistics: References

	(1)	(2)	(3)	(4)
	Average number	*Average share of references to recent research*		
Quality of references	*of references to recent research*	*Home*	*Foreign inside camp*	*Foreign outside camp*
all references	2.593	0.686	0.159	0.150
top 1% references	0.207	0.054	0.012	0.013
top 3% references	0.479	0.126	0.027	0.029
top 5% references	0.702	0.181	0.041	0.040

Notes: In column (1) the table reports the number of references in citing papers published between 1905 and 1930. In columns (2) to (4) the table reports the share of references citing research from home, foreign countries inside the camp, and foreign countries outside the camp. We focus on references to recent research, i.e. research published in the preceding five years. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table 4:
RELATIVE CITATIONS AS MEASURED BY CITATION SHARES

Dependent variable: *Citation Shares to recent research*	(1)	(2)	(3)	(4)	(5) AL sample	(6) CE sample
Foreign *outside* camp × Post 1914	-0.217***	-0.261***				
	(0.033)	(0.040)				
Foreign *outside* camp × WWI			-0.222***	-0.229***	-0.180***	0.047
			(0.025)	(0.034)	(0.030)	(0.037)
Foreign *outside* camp × Boycott			-0.245***	-0.258***	-0.211***	-0.192***
			(0.034)	(0.052)	(0.040)	(0.062)
Foreign *outside* camp × Post Boycott			-0.194***	-0.213***	-0.175***	-0.085
			(0.042)	(0.051)	(0.040)	(0.104)
Foreign *inside* camp × Post 1914	-0.072*	-0.155***				
	(0.041)	(0.051)				
Foreign *inside* camp × WWI			-0.111***	-0.148***	-0.156***	-0.011
			(0.040)	(0.045)	(0.039)	(0.037)
Foreign *inside* camp × Boycott			-0.089**	-0.164***	-0.153**	-0.160**
			(0.042)	(0.057)	(0.059)	(0.072)
Foreign *inside* camp × Post Boycott			-0.048	-0.154**	-0.132**	-0.172
			(0.048)	(0.059)	(0.063)	(0.120)
Paper FE	YES	YES	YES	YES	YES	YES
Camp main effects	YES	YES	YES	YES	YES	YES
Foreign *in/outside* time trends		YES		YES	YES	YES
Observations	105,378	105,378	105,378	105,378	87,060	18,318
Number of citing papers	35,126	35,126	35,126	35,126	29,020	6,106
Within R-squared	0.334	0.335	0.335	0.335	0.429	0.186

Notes: The Table reports estimation results from regression (1) for citing papers published between 1905 and 1930. The dependent variable measures the share of references to research by authors from home, foreign countries inside the camp, and foreign countries outside the camp. We focus on citations to recent research, i.e. research published in the preceding five years, e.g. 1901-1905 for citing papers published in 1905, 1902-1906 for citing papers published in 1906, and so on. The reference/omitted category is the citation share to research from home. Standard errors are clustered at the country-times-field level. Significance levels: ∗∗∗ p<0.01, ∗∗ p<0.05, and ∗ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table 5:
RELATIVE CITATIONS AS MEASURED BY CITATION SHARES: FRONTIER KNOWLEDGE

Dependent variable:	(1)	(2)	(3)	(4)	(5)	(6)
Cit. Sh. to recent frontier research	Frontier: 5%		Frontier: 3%		Frontier: 1%	
Foreign *outside* camp × Post 1914	-0.053***	-0.097***	-0.035***	-0.066***	-0.021***	-0.039***
	(0.017)	(0.021)	(0.013)	(0.013)	(0.006)	(0.007)
Foreign *inside* camp × Post 1914	-0.023	-0.071***	-0.019*	-0.049***	-0.013**	-0.033***
	(0.015)	(0.021)	(0.011)	(0.013)	(0.006)	(0.007)
Paper FE	YES	YES	YES	YES	YES	YES
Camp main effects	YES	YES	YES	YES	YES	YES
Non-frontier knowledge interactions	YES	YES	YES	YES	YES	YES
Foreign *in/outside* time trends		YES		YES		YES
Observations	210,756	210,756	210,756	210,756	210,756	210,756
Number of citing papers	35,126	35,126	35,126	35,126	35,126	35,126
Within R-squared	0.235	0.235	0.299	0.300	0.400	0.400

Notes: The Table reports estimation results from three versions of regression (1) for citing papers published between 1905 and 1930. The dependent variable measures the share of references to frontier and non-frontier research by authors from home, foreign countries inside the camp, and foreign countries outside the camp, i.e. six shares for each citing paper. The Table only reports estimates for frontier research, although the regressions control for non-frontier times post-1914 indicators. For the results reported in columns (1)-(2), frontier research is defined as research that ended up in the top 5% of the subject-level citation distribution until today. Similarly, for the results reported in columns (3)-(4) (and (5)-(6)), frontier research is defined as research that ended up in the top 3% (1%) of the subject-level citation distribution until today. We focus on citations to recent research, i.e. research published in the preceding five years, e.g. 1901-1905 for citing papers published in 1905, 1902-1906 for citing papers published in 1906, and so on. The reference/omitted category is the citation share to frontier research from home. Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table 6:
Relative Citations as Measured by Citation Shares: 1900-1905 Research

Dependent variable: *Citation Shares to 1900-05 research*	(1)	(2)
Foreign *outside* camp × Post 1914	0.130***	-0.056
	(0.039)	(0.045)
Foreign *inside* camp × Post 1914	0.208***	-0.028
	(0.047)	(0.041)
Paper FE	YES	YES
Camp main effects	YES	YES
Foreign *in/outside* time trends		YES
Observations	25,992	25,992
Number of citing papers	8,664	8,664
Within R-squared	0.091	0.096

Notes: The Table reports estimation results from a version of regression (1) for citing papers published between 1905 and 1930. The dependent variable measures the share of references to 1900-1905 research by authors from home, foreign countries inside the camp, and foreign countries outside the camp. We measure citations to a fixed cohort of research: research published between 1900 and 1905. The reference/omitted category is the share of references to 1900-1905 research from home. Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table 7:
SUMMARY STATISTICS: PRODUCTIVITY OF SCIENTISTS

	Mean	Std. Dev.
Number of scientists	8,734	
Number of scientist-year observations	227,084	
Career age in years	7.444	7.708
Publications per year	0.299	1.020
Nobel-nominated papers per year	0.001	0.029
Nomination weighted Nobel-nominated papers per year	0.003	0.152

Notes: The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, and Nobel nomination and award data from Nobelprize.org (2014) (see section 2 for details).

Table 8:
RELIANCE ON FRONTIER KNOWLEDGE: EFFECT ON PUBLICATIONS

Dependent variable: *Number of publications*	(1) Frontier: 1%	(2) Frontier: 3%	(3) Frontier: 5%
Reliance on frontier *OUT* × Post 1914	-1.727***	-0.784***	-0.380*
	(0.638)	(0.282)	(0.220)
Reliance on frontier *IN* × Post 1914	-0.827	-0.363	-0.152
	(0.736)	(0.283)	(0.218)
Reliance on non-frontier knowledge interactions	YES	YES	YES
Career age × field interactions	YES	YES	YES
Year FE	YES	YES	YES
Scientist FE	YES	YES	YES
Observations	227,084	227,084	227,084
Number of scientists	8,734	8,734	8,734
Within R-squared	0.062	0.062	0.062

Notes: The Table reports estimation results from three versions of regression (3) for the panel of university scientists between 1905 and 1930. The dependent variable measures the yearly number of publications in the 161 top journals in our data. The number of publications is normalized by the number of authors and standardized to mean zero and variance one within fields. "Reliance on frontier *OUT*" is the share of pre-1914 references that quote frontier research (1%, 3%, and 5%) from outside the camp. "Reliance on frontier *IN*" is the share of pre-1914 references that quote frontier research (1%, 3%, and 5%) from foreign countries inside the camp. The reference/omitted category is "Reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from textitISI - Web of Science (see section 2 for details).

Table 9:
PRE-WAR RELIANCE ON FRONTIER KNOWLEDGE: PUBLICATIONS - ROBUSTNESS CHECKS

Dependent variable: *Number of publications*	(1) # pub. not normal. by # authors	(2) Exclude chemistry	(3) Control for field × Post 1914	(4) Control for camp × Post 1914	(5) Control for field and camp × Post 1914	(6) Only pub. in own-camp journals
Reliance on 1% frontier *OUT*	-1.775**	-1.697***	-1.683***	-1.495*	-1.414*	-2.181***
× Post 1914	(0.669)	(0.634)	(0.617)	(0.812)	(0.782)	(0.754)
Reliance on 1% frontier *IN*	-0.923	-0.612	-0.784	-0.873	-0.851	-0.621
× Post 1914	(0.730)	(0.773)	(0.733)	(0.734)	(0.743)	(0.884)
Within R-squared	0.066	0.064	0.062	0.062	0.062	0.062
Reliance on 3% frontier *OUT*	-0.813***	-0.791***	-0.751**	-0.605	-0.560	-0.960***
× Post 1914	(0.288)	(0.257)	(0.299)	(0.364)	(0.365)	(0.347)
Reliance on 3% frontier *IN*	-0.454	-0.355	-0.306	-0.448	-0.408	-0.181
× Post 1914	(0.279)	(0.282)	(0.294)	(0.287)	(0.299)	(0.331)
Within R-squared	0.066	0.064	0.062	0.062	0.062	0.061
Reliance on 5% frontier *OUT*	-0.400*	-0.254	-0.382	-0.266	-0.287	-0.370
× Post 1914	(0.222)	(0.213)	(0.274)	(0.250)	(0.286)	(0.295)
Reliance on 5% frontier *IN*	-0.205	-0.025	-0.126	-0.187	-0.166	-0.025
× Post 1914	(0.218)	(0.208)	(0.233)	(0.217)	(0.238)	(0.247)
Within R-squared	0.066	0.064	0.062	0.062	0.062	0.061
Reliance on non-frontier	YES	YES	YES	YES	YES	YES
Career age × field	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Scientist FE	YES	YES	YES	YES	YES	YES
Observations	227,084	197,782	227,084	227,084	227,084	215,046
Number of scientists	8,734	7,607	8,734	8,734	8,734	8,271

Notes: The Table reports estimation results from 18 versions of regression (3) for the panel of university scientists between 1905 and 1930. The dependent variable measures the yearly number of publications in the 161 top journals in our data. For the results reported in column (1), the dependent variable is not normalized by the number of authors but standardized to mean zero and variance one within fields. For the results reported in columns (2)-(5), the dependent variable is normalized by the number of authors and standardized to mean zero and variance one within fields. For the results reported in column (6), the dependent variable only considers publications in home-camp journals and is normalized by the number of authors and standardized to mean zero and variance one within fields. "Reliance on frontier *OUT*" is the share of pre-1914 references that quote frontier research (1%, 3%, and 5%) from outside the camp. "Reliance on frontier *IN*" is the share of pre-1914 references that quote frontier research (1%, 3%, and 5%) from foreign countries inside the camp. The reference/omitted category is "Reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table 10:
Pre-War Reliance on Frontier Knowledge: Effect on Nobel-Nominated Papers

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	Nom. Paper	Nom. Paper weighted by # of nom.	Nom. Paper	Nom. Paper weighted by # of nom.	Nom. Paper	Nom. Paper weighted by # of nom.
	Frontier: 1%		Frontier: 3%		Frontier: 5%	
Reliance on frontier *OUT*	-0.021**	-0.148***	-0.012***	-0.061**	-0.010**	-0.072**
× Post 1914	(0.008)	(0.052)	(0.004)	(0.028)	(0.004)	(0.027)
Reliance on frontier *IN*	-0.005	-0.048	-0.005	-0.021	-0.002	0.012
× Post 1914	(0.008)	(0.041)	(0.004)	(0.018)	(0.003)	(0.017)
Reliance on non-frontier	YES	YES	YES	YES	YES	YES
Career age × field	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Scientist FE	YES	YES	YES	YES	YES	YES
Observations	227,084	227,084	227,084	227,084	227,084	227,084
Number of scientists	8,734	8,734	8,734	8,734	8,734	8,734
Within R-squared	0.001	0.001	0.001	0.001	0.001	0.001

Notes: The Table reports estimation results from six versions of regression (5) for the panel of university scientists between 1905 and 1930. The dependent variable in odd columns is an indicator that equals one if a scientist published a Nobel-nominated paper in a certain year, and zero for all other years. The dependent variable in even columns weighs the Nobel-nominated paper indicator by the number of nominations in the two years before a candidate's last nomination. "Reliance on frontier *OUT*" is the share of pre-1914 references that quote frontier research (1%, 3%, and 5%) from outside the camp. "Reliance on frontier *IN*" is the share of pre-1914 references that quote frontier research (1%, 3%, and 5%) from foreign countries inside the camp. The reference/omitted category is "Reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, and Nobel nomination and award data from Nobelprize.org (2014) (see section 2 for details).

Table 11:
PRE-WAR RELIANCE ON FRONTIER KNOWLEDGE: NOBEL-NOMINATED PAPERS - ROBUSTNESS CHECKS

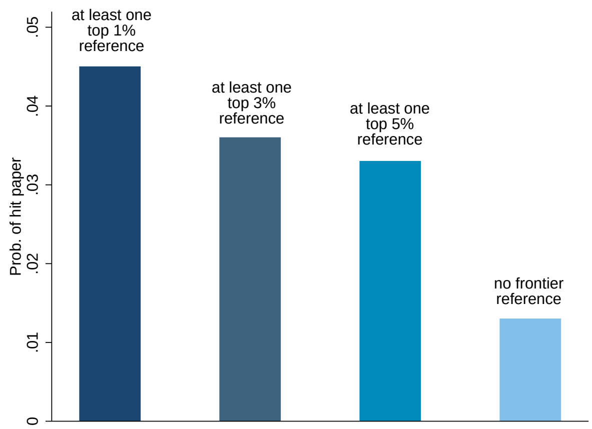
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable:	Nom. Paper	Nom. Paper weighted by # of nom.	Nom. Paper	Nom. Paper weighted by # of nom.	Nom. Paper	Nom. Paper weighted by # of nom.	Nom. Paper	Nom. Paper weighted by # of nom.
	Exclude chemistry		Control for field × Post 1914		Control for camp × Post 1914		Control for field and camp × Post 1914	
Reliance on 1% frontier *OUT*	-0.020**	-0.129**	-0.019**	-0.140***	-0.019**	-0.154**	-0.018*	-0.150**
× Post 1914	(0.008)	(0.049)	(0.008)	(0.051)	(0.009)	(0.070)	(0.009)	(0.072)
Reliance on 1% frontier *IN*	-0.007	-0.063	-0.004	-0.034	-0.005	-0.047	-0.004	-0.031
× Post 1914	(0.008)	(0.044)	(0.009)	(0.049)	(0.008)	(0.040)	(0.009)	(0.047)
Within R-squared	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Reliance on 3% frontier *OUT*	-0.012***	-0.045	-0.012***	-0.059**	-0.011**	-0.059*	-0.010**	-0.059*
× Post 1914	(0.004)	(0.030)	(0.004)	(0.027)	(0.004)	(0.031)	(0.004)	(0.031)
Reliance on 3% frontier *IN*	-0.006	-0.021	-0.005	-0.015	-0.006	-0.022	-0.006	-0.015
× Post 1914	(0.005)	(0.021)	(0.005)	(0.020)	(0.004)	(0.016)	(0.004)	(0.017)
Within R-squared	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Reliance on 5% frontier *OUT*	-0.011**	-0.064**	-0.009*	-0.068**	-0.009**	-0.072**	-0.009*	-0.070**
× Post 1914	(0.005)	(0.028)	(0.005)	(0.028)	(0.004)	(0.029)	(0.005)	(0.029)
Reliance on 5% frontier *IN*	-0.003	0.014	-0.002	0.016	-0.003	0.012	-0.002	0.016
× Post 1914	(0.003)	(0.018)	(0.003)	(0.018)	(0.002)	(0.018)	(0.003)	(0.019)
Within R-squared	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Reliance on non-frontier	YES	YES	YES	YES	YES	YES	YES	YES
Career age × field	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Scientist FE	YES	YES	YES	YES	YES	YES	YES	YES
Observations	197,782	197,782	227,084	227,084	227,084	227,084	227,084	227,084
Number of scientists	7,607	7,607	8,734	8,734	8,734	8,734	8,734	8,734

Notes: The Table reports estimation results from 24 versions of regression (5) for the panel of university scientists between 1905 and 1930. The dependent variable in odd columns is an indicator that equals one if a scientist published a Nobel-nominated paper in a certain year, and zero for all other years. The dependent variable in even columns weighs the Nobel-nominated paper indicator by the number of nominations in the two years before a candidate's last nomination. "Reliance on frontier *OUT*" is the share of pre-1914 references that quote frontier research (1%, 3%, and 5%) from outside the camp. "Reliance on frontier *IN*" is the share of pre-1914 references that quote frontier research (1%, 3%, and 5%) from foreign countries inside the camp. The reference/omitted category is "Reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, and Nobel nomination and award data from Nobelprize.org (2014) (see section 2 for details).

A Appendix

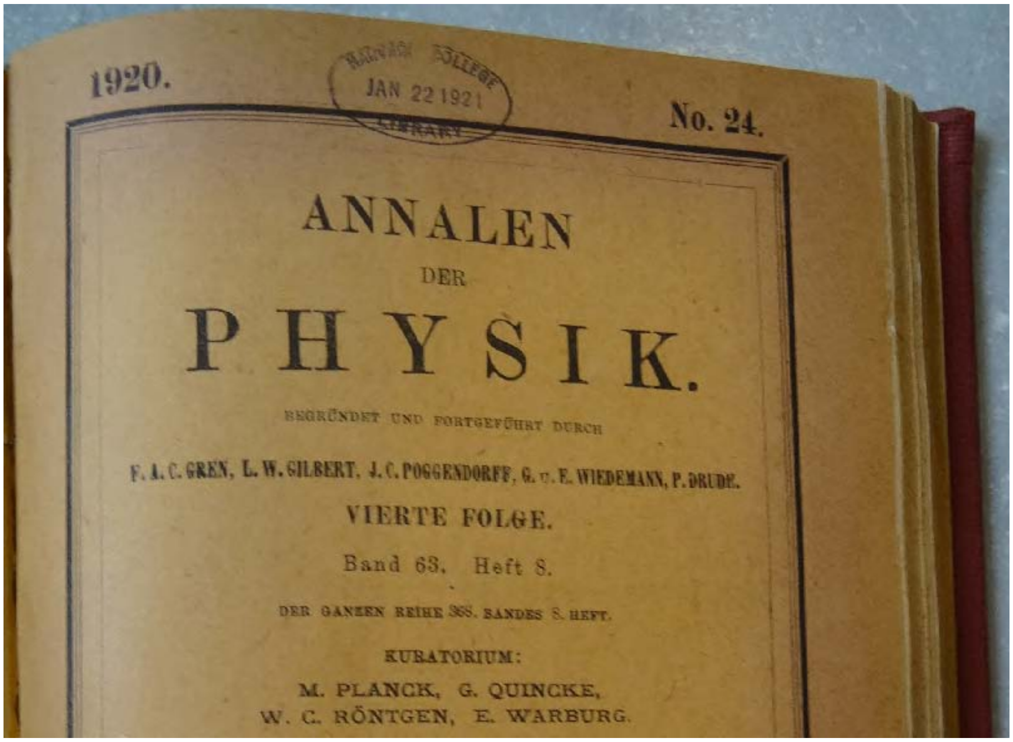
A.1 Appendix Figures

Figure A.1:
Probability of Hit Paper Depending on the Quality of Cited References



Notes: The Figure plots the probability that a paper becomes a hit, i.e. ends up in the top 1 percent of the field-level citation distribution until today. Differently from Figure 1, the field-level citation distribution is not calculated within the sample of papers used in the analysis, but for all papers published in the 161 top journals between 1905 and 1930. Each bar reports the probability of becoming a hit, depending on the quality of cited references. Only references to research published in the five years preceding the publication of the citing paper are considered. Self-citations are excluded. The bar "at least one top 1% reference" shows the probability that the citing paper becomes a hit if it cites at least one reference that ends up in the top 1% of the citation distribution until today. The bar "at least one top 3% reference" shows the probability that the citing paper becomes a hit if it cites at least one reference that ends up in the top 3% of the citation distribution, and so on. The bar "no frontier reference" shows the probability that the citing paper becomes a hit if it does not cite references that end up in the top 5% of the citation distribution. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure A.2: Example Entry Stamp Harvard Library


1920. No. 24.

ANNALEN
DER
PHYSIK.

BEGRÜNDET UND FORTGEFÜHRT DURCH

F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF, G. u. E. WIEDEMANN, P. DRUDE.

VIERTE FOLGE.

Band 63. Heft 8.

DER GANZEN REIHE 368. BANDES 8. HEFT.

KURATORIUM:

M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, E. WARBURG.

Notes: The stamp at the top of the page indicates the arrival date of this issue of the *Annalen der Physik* at the Harvard library.

Figure A.3:
SAMPLE PAGE OF MINERVA

Cambridge (Massachusetts, Ver. St. A.).
HARVARD UNIVERSITY (1636).

Geschichte, Verfassung, Organisation, Aufnahme, Grade, Gebühren: ☞.

JAHRESHAUSHALT. Vermögen nach d. Ausweis von 1912: \$ 25752720.39. Privatschenkungen 1912: \$ 932409.21 nebst \$ 771772.20 zum sofortigen Gebrauch. Gesamteinnahmen einschliessl. »gifts for immediate use« (1911/12): \$ 2930752.89, Gesamtausgaben \$ 2503658.03, Ausgaben für Unterrichtszwecke (Gehälter, usw.) \$ 1292344.28; Stipendien u. Preise, usw. \$ 192001.81.

BEGINN d. akad. Jahres: 22. September, Schluss: 18. Juni.

Zahl der Lehrer (1912/13): 774; der Studierenden: 4279 (College 2308, Graduate Schools 595, Graduate School of Business Administration 107, Divinity School 48, Law School 741, Med. School 290, Dental School 190); dazu 9 Extension Students und 1187 Summer School 1912, ab doppelt gezählt 251 = Summe 5224. — *President:* Abbott Lawrence Lowell. — *Secretaries to the Corporation:* G. Peabody Gardner, jr.; Francis Welles Hunnewell; William Phillips.

— PROFESSORS:
Charles S. Sargent: *Baumkult.*
Edward Charles Pickering: *Praktische Astronomie.*
William Gilson Farlow: *Botanik der Kryptogamen.*
Edw. Young Hincks: *Bibl. Theol.*
William Henry Ryder: *Neues Testament.*
Edward H. Bradford: *Orthop. Chirurgie* (Dean of the Faculty of Medicine and of the Medical School).
Joseph D. Brannan: *Rechtswiss.*
Charles A. Brackett: *Zahnpath.*
Thomas M. Rotch: *Kinderheilk.*
Ephr. Emerton: *Kirchengesch.*
Charles R. Lanman: *Sanskrit.*
Edward Laurens Mark: *Anat.*
Eugene H. Smith: *Zahntechnik* (Dean of the Dental School).
Charles S. Minot: *Vergl. Anat.*
George F. Moore: *Gesch. d. Rel.*
Edward S. Sheldon: *Rom. Phil.*
Horatio Stevens White: *Deutsch.*
Robert W. Willson: *Astronom.*
Charles M. Green: *Geburtshilfe.*
Edward Dyer Peters: *Metallurg.*
Edward Cornelius Briggs: *Zahn-Materia medica und Therapie.*
Le Baron Russell Briggs: *Rhetorik u. Beredsamkeit* (Dean of the Faculty of Arts and Sciences).
William Thomas Councilman: *Pathologische Anatomie.*
Kuno Francke: *German. Kulturgeschichte.*
Edwin Herbert Hall: *Physik.*
David Gordon Lyon: *Hebräisch und andere oriental. Sprachen.*
George H. Monks: *Mund-Chirur.*
Josiah Royce: *Gesch. d. Philos.*
Myles Standish: *Ophthalmolog.*
Harold Clarence Ernst: *Bakter.*
Benjamin Osgood Peirce: *Mathematik und Naturphilosophie.*

Notes: A sample page from *Minerva - Handbuch der Gelehrten Welt* (see section 2 for details).

Figure A.4:
THE WORLD OF SCIENCE IN 1914

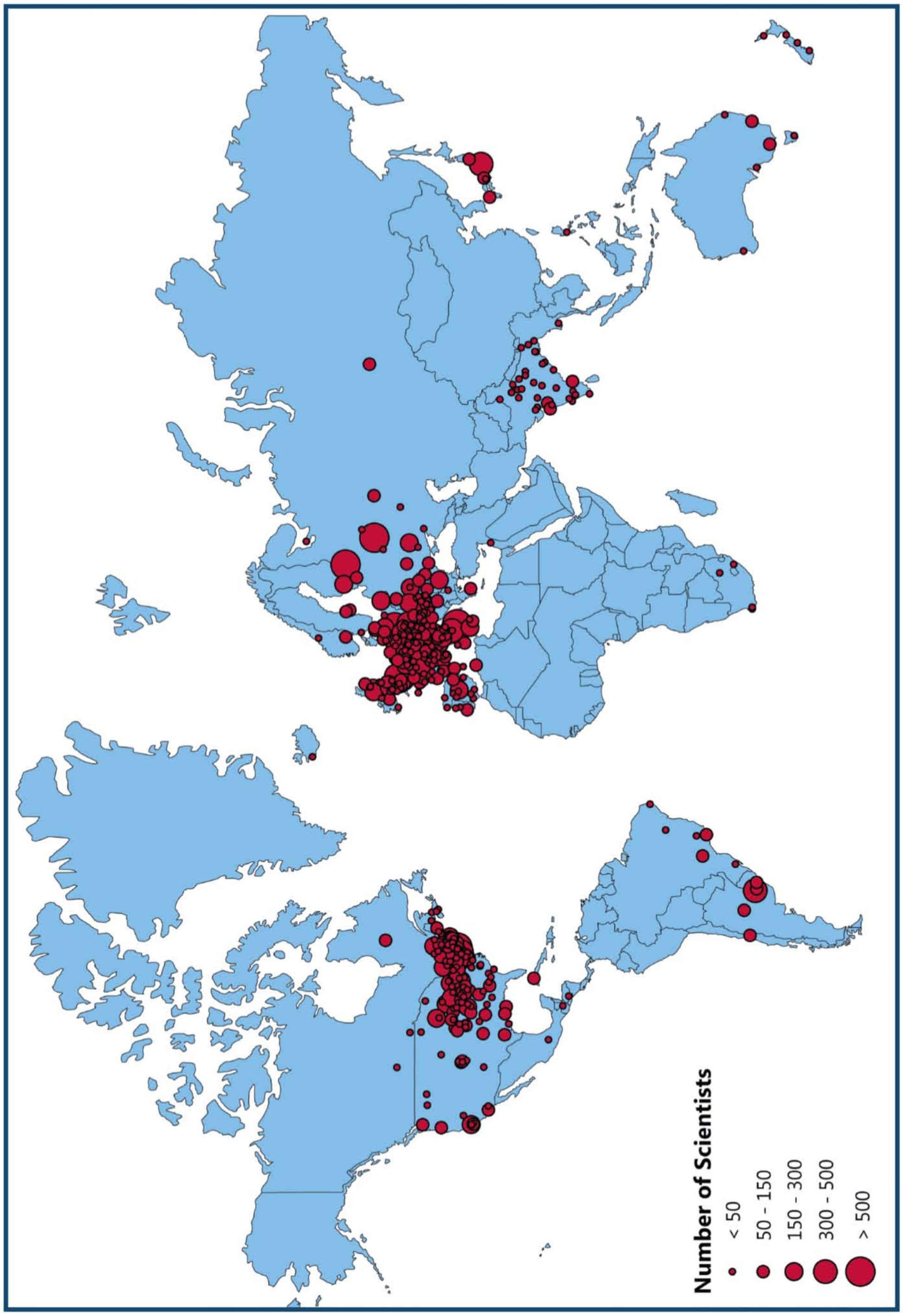
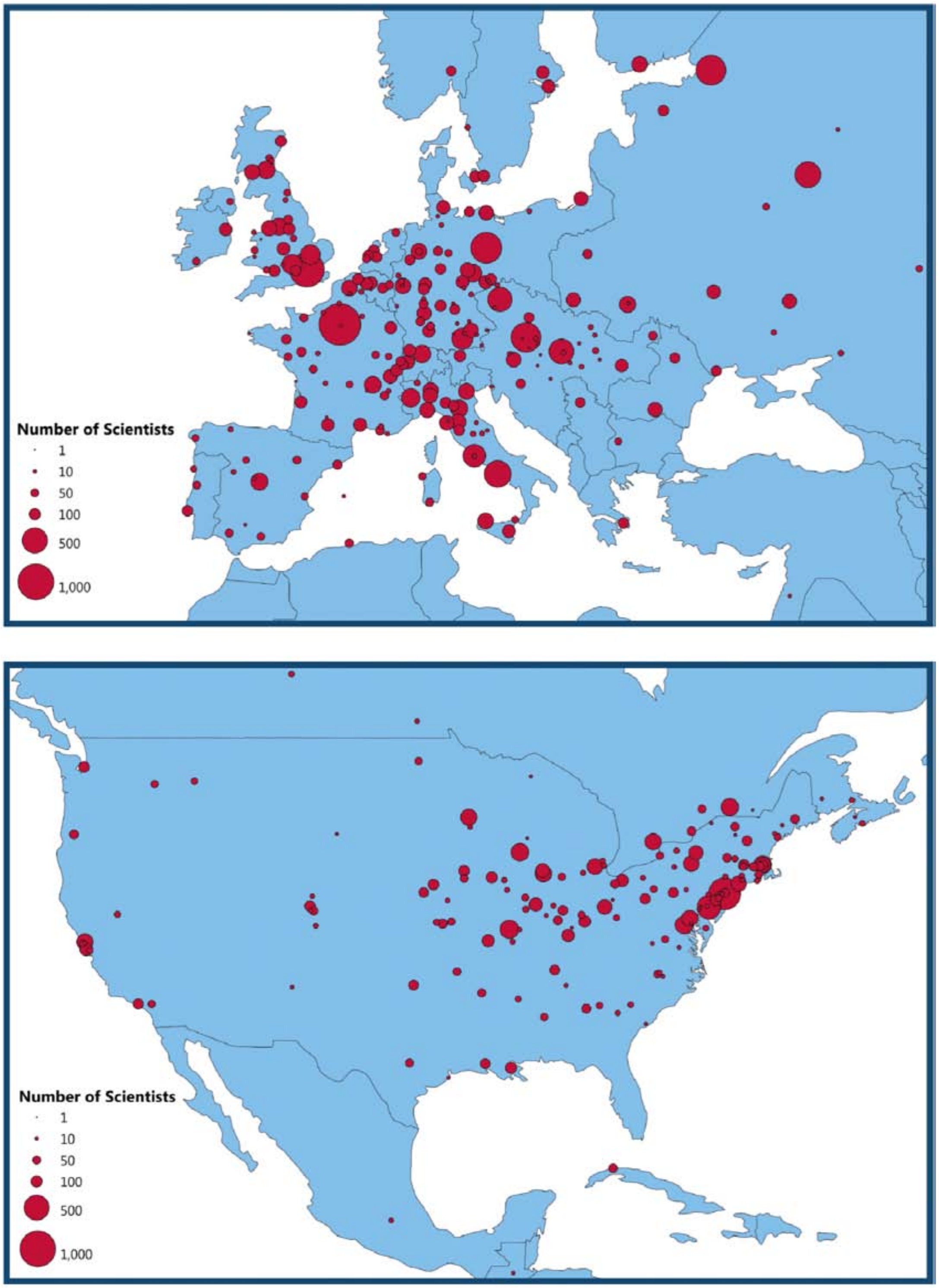


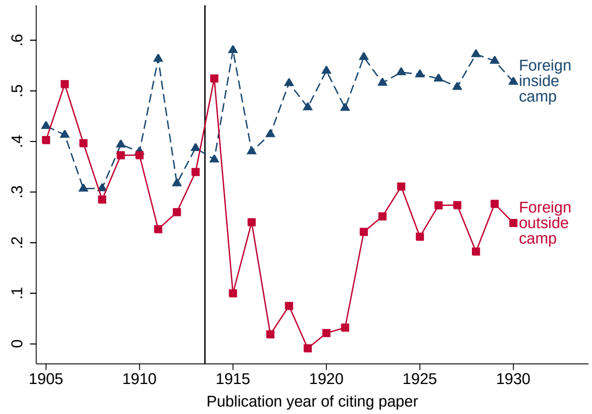
Figure A.4:
THE WORLD OF SCIENCE IN 1914



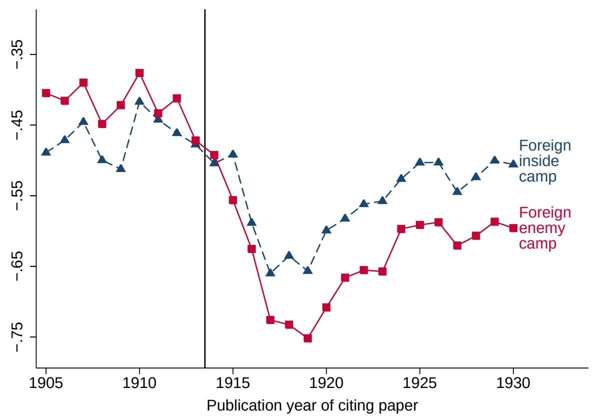
Notes: The map shows the total number of professors in all fields by city in 1914. Dot sizes are proportional to the number of professors. The scientist census data were collected by the authors from *Minerva - Handbuch der Gelehrten Welt* (see section 2 for details).

Figure A.5:
CITATION SHARES: ADDITIONAL ROBUSTNESS CHECKS

(a) Excluding U.S., German, and British Citing Papers

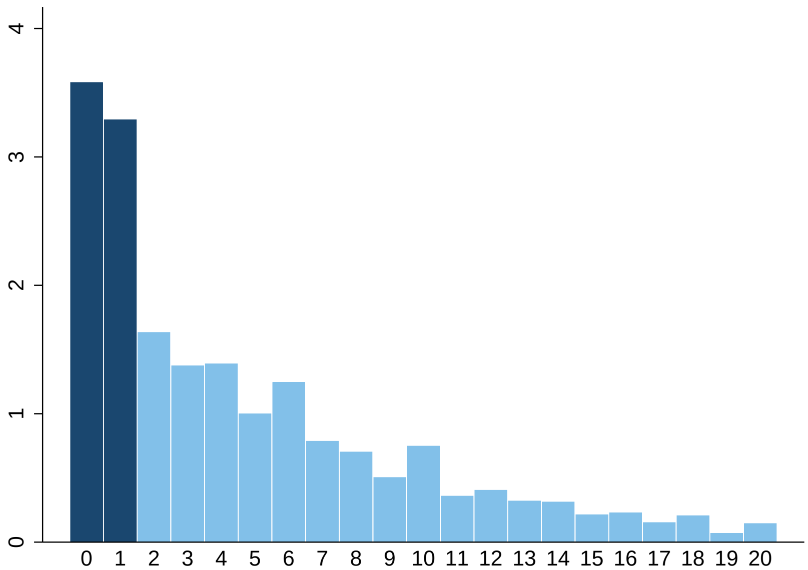


(b) Relative Citation Shares to Enemy papers



Notes: The Figure in panel (a) plots parameter estimates of regression (2), for a sample of papers published by scientists in smaller Allied or Central countries, i.e. scientists outside of the United States, Germany, and Britain. The "Foreign outside camp" line reports point estimates (ω_τ) that measure the share of citations to research from outside the camp, relative to research from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure the share of citations to research published by foreign authors inside the camp, relative to research published at home. The Figure in panel (b) plots parameter estimates of a version of regression (2) in which the citation shares to research written by scientists from outside the camp are further split into the share citing research from enemy countries and into the share citing research from other foreign countries (results not reported in the figure). In both panels, we focus on citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures the relative share of citations to research published between 1901 and 1905. The second dot (1906) measures the relative share of citations to research published between 1902 and 1906, and so on. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure A.6:
Nominations per Year for Eventual Nobel Prize Winners



Notes: The Figure plots the average number of nominations per year for Nobel Laureates, relative to the year of the award. For example, the first bar from the left (0) shows that Nobel Laureates on average receive 3.6 nominations in the winning year. Similary, the second bar from the left (1) shows that Nobel Laureates receive on average 3.3 nominations the year before the winning year. The data were collected by the authors from Nobelprize.org (2014) and include 131 Nobel Prize winners.

A.2 Appendix Tables

Table A.1:
Summary Statistics: Scientists

	Minerva 1900	*Minerva 1914*
Panel (a): Scholars from all fields		
Number of universities	569	973
Total number of university scholars	24,166	42,226
Scholars with name information	23,917	36,777
Panel (b): Scientists from all fields		
Total scientists (5 fields)	10,133	15,891
Medicine	5,413	8,829
Biology	1,486	2,353
Chemistry	1,317	2,077
Physics	1,167	1,626
Mathematics	1,062	1,440

Notes: Panel (a) reports university professors in all fields. Panel (b) focuses on university professors in the five scientific fields used throughout the paper. The entry of "Total scientists (5 fields)" is smaller than the sum of the 5 fields below because some scientists work in multiple fields. The data were collected by the authors from two volumes (1900 and 1914) of *Minerva - Handbuch der Gelehrten Welt* (see section 2 for details).

Table A.2:
Solvay Conferences in Physics: Allies and Centrals

	1911	1913	1921	1924	1927	1930
ALLIES	M. Brillouin (FR)	W. Barlow (UK)	C. Barkla (UK, ’17)	E. Bauer (FR)	W. Bragg (UK, ’15)	E. Bauer (FR)
	M. Curie (FR, ’03, ’11)	W. Bragg (UK, ’15)	W. Bragg (UK, ’15)	W. Bragg (UK, ’15)	L. Brillouin (FR)	L. Brillouin (FR)
	M. de Broglie (FR)	M. Brillouin (FR)	L. Brillouin (FR)	P. Bridgman (USA, ’46)	L. de Broglie (FR, ’29)	A. Cotton (FR)
	R. Goldschmidt (BE)	M. Curie (FR, ’03, ’11)	M. Brillouin (FR)	L. Brillouin (FR)	A. Compton (USA, ’27)	M. Curie (FR, ’03, ’11)
	É. Herzen (BE)	M. de Broglie (FR)	M. Curie (FR, ’03, ’11)	M. Brillouin (FR)	M. Curie (FR, ’03, ’11)	C. Darwin (UK)
	G. Hostelet (BE)	R. Goldschmidt (BE)	M. de Broglie (FR)	W. Broniewski (PL)	T. de Donder (BE)	T. de Donder (BE)
	J. Jeans (UK)	L. Gouy (FR)	É. Herzen (BE)	M. Curie (FR, ’03, ’11)	P. Dirac (UK, ’33)	P. Dirac (UK, ’33)
	P. Langevin (FR)	É. Herzen (BE)	P. Langevin (FR)	T. de Donder (BE)	R. Fowler (UK)	J. Errera (BE)
	J. Perrin (FR, ’26)	G. Hostelet (BE)	J. Larmor (UK)	E. Hall (USA)	É. Henriot (BE)	E. Fermi (ITA, ’38)
	H. Poincaré (FR)	J. Jeans (UK)	A. Michelson (USA, ’07)	É. Henriot (BE)	É. Herzen (BE)	É. Henriot (BE)
	E. Rutherford (UK, ’08)	P. Langevin (FR)	R. Millikan (USA, ’23)	É. Herzen (BE)	P. Langevin (FR)	É. Herzen (BE)
	E. Solvay (BE)	W. Pope (UK)	J. Perrin (FR, ’26)	P. Langevin (FR)	I. Langmuir (USA, ’32)	P. Kapitza (UK)
		E. Rutherford (UK, ’08)	O. Richardson (UK, ’28)	F. Lindemann (UK)	A. Piccard (BE)	P. Langevin (FR)
		J. J. Thomson (UK, ’06)	E. Rutherford (UK, ’08)	A. Piccard (BE)	O. Richardson (UK, ’28)	C. Manneback (BE)
		R. Wood (USA)	E. Solvay (BE)	O. Richardson (UK, ’28)	E. van Aubel (BE)	A. Piccard (BE)
			E. van Aubel (BE)	W. Rosenhain (UK)	J. Verschaffelt (BE)	O. Richardson (UK, ’28)
			P. Weiss (FR)	E. Rutherford (UK, ’08)	C. Wilson (UK, ’27)	J. Van Vleck (USA, ’77)
				E. van Aubel (BE)		J. Verschaffelt (BE)
				J. Verschaffelt (BE)		P. Weiss (FR)
CENTRALS	A. Einstein (AU, ’21)	E. Grüneisen (GE)			M. Born (GE, ’54)	P. Debye (GE, ’36)
	F. Hasenöhrl (AU)	F. Hasenöhrl (AU)			P. Debye (GE, ’36)	A. Einstein (GE, ’21)
	F. Lindemann (GE)	F. Lindemann (GE)			A. Einstein (GE, ’21)	W. Gerlach (GE)
	W. Nernst (GE, ’20)	W. Nernst (GE, ’20)			W. Pauli (GE, ’45)	W. Heisenberg (GE, ’32)
	M. Planck (GE, ’18)	H. Rubens (GE)			M. Planck (GE, ’18)	A. Sommerfeld (GE)
	H. Rubens (GE)	A. Sommerfeld (GE)				O. Stern (GE, ’43)
	A. Sommerfeld (GE)	W. Voigt (GE)				
	E. Warburg (GE)	E. Warburg (GE)				
	W. Wien (GE, ’11)	W. Wien (GE, ’11)				

Table A.2:
SOLVAY CONFERENCES IN PHYSICS: NEUTRALS AND REST

	1911	*1913*	*1921*	*1924*	*1927*	*1930*
NEUTRALS	M. Knudsen (DK) H. Lorentz (NE, '02) H. Onnes (NE, '13)	A. Einstein (SWZ, '21) H. Lorentz (NE, '02) M. Knudsen (DK) H. Onnes (NE, '13) J. Verschaffelt (NE) M. von Laue (SWZ, '14) P. Weiss (SWZ)	W. de Haas (NE) P. Ehrenfest (NE) M. Knudsen (DK) H. Lorentz (NE, '02) H. Onnes (NE, '13) K. Siegbahn (SWE, '24) J. Verschaffelt (NE) P. Zeeman (NE, '02)	P. Debye (SWZ, '36) G. de Hevesy (DK, '43) W. Keesom (NE) M. Knudsen (DK) H. Lorentz (NE, '02) H. Onnes (NE, '13) E. Schrödinger (SWZ, '33)	N. Bohr (DK, '22) P. Ehrenfest (NE) C. Guye (SWZ) W. Heisenberg (DK, '32)★ M. Knudsen (DK) H. Kramers (NE) H. Lorentz (NE, '02) E. Schrödinger (SWZ, '33)★	N. Bohr (DK, '22) B. Cabrera (SPA) W. de Haas (NE) B. Felipe (SPA) C. Guye (SWZ) M. Knudsen (DK) H. Kramers (NE) W. Pauli (SWZ, '45) P. Zeeman (NE, '02)
REST				A. Joffé (RUS)		J. Dorfman (RUS) P. Kapitsa (RUS, '78)

Notes: The Table reports delegates at each textitSolvay Conference in Physics between 1911 and 1930. In brackets, after the name, we report the country of residence at the moment of the conference and the year when a delegate won a Nobel prize. The data were collected by the authors from Mehra (1975) (see Appendix F for details).
★ Even though classified as Neutrals in Mehra's data, Heisenberg and Schrödinger were de facto in the German system in 1927. Heisenberg had a joint appointment at the German University of Göttingen and the Danish University of Copenhagen and moved to a permanent position at the German University of Leipzig in 1927. Schrödinger moved to the German University of Berlin in 1927.

Table A.3:
LIST OF SCIENTIFIC JOURNALS

Country	Field	Journal title
USA	General	American Journal of Science
USA	General	Proceedings of The National Academy of Sciences of The United States of America
USA	General	Proceedings of the American Academy of Arts and Sciences
USA	General	Review of Scientific Instruments
USA	General	Science
USA	Medicine	American Journal of Physiology
USA	Medicine	Archives of Pathology and Laboratory Medicine
USA	Medicine	Archives of pathology
USA	Medicine	Contributions to Embryology
USA	Medicine	Journal of Experimental Medicine
USA	Medicine	Journal of Infectious Diseases
USA	Medicine	Journal of Urology
USA	Medicine	Journal of the American Medical Association
USA	Medicine	Medicine
USA	Medicine	New England Journal of Medicine
USA	Bio./Med.	Anatomical Record
USA	Bio./Med.	Endocrinology
USA	Bio./Med.	Genetics
USA	Bio./Med.	Journal of Clinical Endocrinology
USA	Bio./Med.	Journal of General Physiology
USA	Bio./Med.	Journal of Immunology
USA	Bio./Med.	Journal of Morphology
USA	Bio./Med.	Journal of Morphology and Physiology
USA	Bio./Med.	Physiological Reviews
USA	Bio./Med.	Proceedings of The Society for Experimental Biology And Medicine
USA	Biology	American Journal of Anatomy
USA	Biology	American Journal of Botany
USA	Biology	American Journal of Pathology
USA	Biology	American Naturalist
USA	Biology	Biological Bulletin
USA	Biology	Botanical Gazette
USA	Biology	Ecology
USA	Biology	Journal of Bacteriology
USA	Biology	Journal of Economic Entomology
USA	Biology	Journal of Experimental Zoology
USA	Biology	Journal of Medical Research
USA	Biology	Journal of heredity
USA	Biology	Phytopathology
USA	Biology	Plant Physiology
USA	Biology	Quarterly Review of Biology

Table A.3:
LIST OF SCIENTIFIC JOURNALS

Country	Field	Journal title
USA	Pharmac.	Journal of Pharmacology and Experimental Therapeutics
USA	Biochem.	Journal of Biological Chemistry
USA	Biochem.	Stain technology
USA	Chemistry	Chemical Reviews
USA	Chemistry	Industrial and Engineering Chemistry
USA	Chemistry	Industrial and Engineering Chemistry, Analytical Edition
USA	Chemistry	Journal of The American Chemical Society
USA	Chemistry	Organic Syntheses
USA	Chemistry	Transactions of The American Institute of Chemical Engineers
USA	Phys. Chem.	Journal of Physical Chemistry
USA	Physics	Journal of the Optical Society of America
USA	Physics	Journal of the Optical Society of America and review of scientific instruments
USA	Physics	Physical Review
USA	Physics	Review of Modern Physics
USA	Math. Phys.	Proceedings of the IRE
USA	Mathematics	American Journal of Mathematics
USA	Mathematics	Annals of Mathematical Statistics
USA	Mathematics	Annals of Mathematics
USA	Mathematics	Journal of the American Statistical Association
USA	Mathematics	Journal of the Franklin Institute
USA	Mathematics	Publications of the American Statistical Association
USA	Mathematics	Quarterly Publications of the American Statistical Association
USA	Mathematics	Transactions of The American Mathematical Society
UK	General	Nature
UK	General	Philosophical Magazine
UK	General	Proceedings of The Cambridge Philosophical Society
UK	General	Proceedings of the Royal Society of London
UK	Medicine	Journal of Anatomy
UK	Medicine	Journal of Pathology and Bacteriology
UK	Medicine	Lancet
UK	Medicine	Quarterly Journal of Medicine
UK	Bio./Med.	British Journal of Experimental Pathology
UK	Bio./Med.	Quarterly Journal of Experimental Physiology and Cognate Medical Sciences
UK	Bio./Med.	Quarterly journal of experimental physiology
UK	Biology	Annals of Applied Biology
UK	Biology	Annals of Botany
UK	Biology	Annals of Eugenics
UK	Biology	Biological Reviews of the Cambridge Philosophical Society
UK	Biology	Biological reviews and Biological Proceedings of the Cambridge Philos. Soc.
UK	Biology	British journal of experimental biology
UK	Biology	Journal of Ecology

Table A.3:
LIST OF SCIENTIFIC JOURNALS

Country	Field	Journal title
UK	Biology	Journal of Experimental Biology
UK	Biology	Journal of Genetics
UK	Biology	Philos. Trans. of the Royal Soc. of Lond. Ser. B, Cont. Papers of a Biolog. Charac.
UK	Biology	Philosoph. Transact. of the Royal Soc. of London Ser. B-Biol. Sciences
UK	Biology	Proceedings of the Zoological Society of London
UK	Biology	Proceedings of the Cambridge Philosophical Society-Biological Sciences
UK	Biology	Proceedings of the Royal Soc. of London Series B, Cont. Papers of a Biol. Charac.
UK	Biology	Proceedings of the Royal Society of London Series B-Biological Sciences
UK	Biology	Proce. of the Zoological Society of London Series A-General and Experimental
UK	Biology	Proce. of the Zoolog. Soc. of London Series B-Systematic and Morphological
UK	Biology	Quarterly Journal of Microscopical Science
UK	Biochem.	Biochemical Journal
UK	Chemistry	Journal of the Chemical Society
UK	Chemistry	Transactions of the Faraday Society
UK	Physics	Astrophysical Journal
UK	Physics	Monthly Notices of the Royal Astronomical Society
UK	Physics	Proceedings of the Physical Society Of London
UK	Physics	Proceedings of the Physical Society
UK	Math. Phys.	Phil. Trans. of the Roy. Soc. of Lond. Ser. A, Cont. Pap. of a Math. or Phys. Char.
UK	Math. Phys.	Philos. Trans. of the Royal Society of London Series A-Math. and Phys. Sciences
UK	Math. Phys.	Proce. of the Roy. Soc. of Lon. Ser. A, Cont. Papers of a Math. and Phys. Char.
UK	Math. Phys.	Proce. of the Roy. Soc. of Lon. Ser. A-Math. and Phys. Sciences
UK	Mathematics	Biometrika
UK	Mathematics	Journal of the Royal Statistical Society
UK	Mathematics	Proceedings of the London Mathematical Society
Germany	General	Archiv für Experimentelle Pathologie und Pharmakologie
Germany	General	Hoppe-Seylers Zeitschrift fur Physiologische Chemie
Germany	General	Naturwissenschaften
Germany	General	Naunyn-Schmied. Archiv für Experiment. Pathologie Und Pharmakologie
Germany	General	Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften
Germany	Medicine	Archiv für Patholog. Anatomie und Physiol. und für Klinische Medicin
Germany	Medicine	Journal für Psychologie und Neurologie
Germany	Medicine	Virch. Archiv für Patholog. Anato. und Physiol. und für Klinis. Medizin
Germany	Medicine	Zeitschrift für die Gesamte Neurologie und Psychiatrie
Germany	Bio./Med.	Archiv für Mikroskopische Anatomie
Germany	Bio./Med.	Archiv für Mikroskopische Anatomie und Entwicklungsgeschichte
Germany	Bio./Med.	Archiv für die Gesamte Physiologie des Menschen und der Tiere
Germany	Bio./Med.	Archiv für Mikroskopische Anatomie und Entwicklungsmechanik
Germany	Bio./Med.	Beitrage zur Pathologischen Anatomie und zur Allgemeinen Pathologie
Germany	Bio./Med.	Pflugers Archiv für die Gesamte Physiologie des Menschen und der Tiere
Germany	Bio./Med.	Wilhelm Roux' Archiv für Entwicklungsmechanik der Organismen

Table A.3:
LIST OF SCIENTIFIC JOURNALS

Country	Field	Journal title
Germany	Biology	Archiv für Entwicklungsmechanik der Organismen
Germany	Biology	Archiv für Experimentelle Zellforschung
Germany	Biology	Zeitschrift für Biologie
Germany	Biology	Zeitschrift für Wissenschaftliche Zoologie
Germany	Biochem.	Biochemische Zeitschrift
Germany	Chemistry	Berichte der Deutschen Chemischen Gesellschaft
Germany	Chemistry	Journal für Praktische Chemie-Leipzig (chk 1944)
Germany	Chemistry	Justus Liebigs Annalen der Chemie
Germany	Chemistry	Kolloid Zeitschrift
Germany	Chemistry	Zeitschrift für Anorganische und Allgemeine Chemie
Germany	Chemistry	Zeitschrift für Elektrochemie
Germany	Chemistry	Zeitschrift für Elektrochemie und Angewandte Physikalische Chemie
Germany	Chemistry	Zeitschrift für Kristallographie
Germany	Chemistry	Zeitschrift für Krystallographie und Mineralogie
Germany	Chemistry	Zeitschrift für Anorganische Chemie
Germany	Phys. Chem.	Zeitschrift für Physikalische Chemie Stochiometrie und Verwandtschaftslehre
Germany	Phys. Chem.	Zeitsch. für Physik. Chem.-Abteil. A-Chem. Therm. Kinet. Elektroche. Eigens.
Germany	Phys. Chem.	Zeitsch. für Physik. Chem.-Abteil. B-Chem. der Elementarproz. Aufb. der Mater.
Germany	Physics	Annalen der Physik
Germany	Physics	Physikalische Zeitschrift
Germany	Physics	Zeitschrift für Physik
Germany	Math. Phys.	Sitzungsbe. der Preussi. Akad. der Wissensch. Physik.-Mathem. Klasse
Germany	Mathematics	Journal für die Reine und Angewandte Mathematik
Germany	Mathematics	Mathematische Annalen
Germany	Mathematics	Mathematische Zeitschrift
Germany	Mathematics	Zeitschrift für Angewandte Mathematik und Mechanik
France	General	Comptes Rendus Hebdomadaires des Seances de L'Academie des Sciences
France	Biology	Comptes Rendus des Seances de la Societe de Biologie et de ses Filiales
France	Chemistry	Annales de Chimie France
France	Phys. Chem.	Annales de Chemie et de Physique
France	Physics	Journal de Physique et le Radium
Netherlands	General	Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen
Netherlands	General	Proce. of the Koninkl. Nederlan. Akad. van Wetenschap. te Amsterdam
Netherlands	Chemistry	Recueil des Travaux Chimiques des Pays-Bas
Netherlands	Chemistry	Recueil des Travaux Chimiques des Pays-Bas et de la Belgique
Sweden	Bio./Med.	Hereditas
Sweden	Bio./Med.	Skandinavisches Archiv fur Physiologie
Sweden	Mathematics	Acta Mathematica
Switzerland	Chemistry	Helvetica Chimica Acta

Notes: The Table reports the 161 journals used in the analysis ordered by country and field. Journal data were collected by the authors from *ISI - Web of Science* (see section 2 for details).

Table A.4:
Summary Statistics: Publications by Journal Country

	(1)	(2)	(3)	(4)	(5)
	Share publications in journal country				
	U.S.A.	*U.K.*	*France*	*Germany*	*Others*
Allies:					
U.S.A.	**0.93**	0.04	0.00	0.03	0.00
U.K.	0.11	**0.83**	0.00	0.05	0.00
Canada	**0.71**	0.25	0.00	0.04	0.00
Japan	0.31	0.17	0.00	**0.51**	0.01
France	0.20	0.14	**0.38**	0.26	0.02
Italy	0.10	0.10	0.00	**0.79**	0.00
Australia	0.38	**0.57**	0.00	0.05	0.00
Poland	0.20	0.27	0.00	**0.48**	0.05
Ireland	0.34	**0.59**	0.00	0.07	0.00
Belgium	0.14	0.06	**0.64**	0.14	0.02
New Zealand	0.23	**0.73**	0.00	0.03	0.00
Rumania	0.11	0.00	0.21	**0.68**	0.00
Brazil	0.00	0.11	0.00	**0.89**	0.00
South Africa	0.14	**0.71**	0.00	0.14	0.00
Greece	0.00	0.00	0.00	**1.00**	0.00
Portugal	**1.00**	0.00	0.00	0.00	0.00
Centrals:					
Germany	0.01	0.01	0.00	**0.98**	0.00
Austria	0.03	0.01	0.00	**0.95**	0.01
Hungary	0.05	0.01	0.00	**0.92**	0.01

Notes: The Table reports the distribution of published papers across journal countries. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.5:
Citation Shares Relative to Home: Citations to Any Work

	Param. Est.	*Std. Err.*		*Param. Est.*	*Std. Err.*
Foreign outside × 1905	-0.3228051	0.0610700	Foreign inside × 1905	-0.4890254	0.0450000
Foreign outside × 1906	-0.3397578	0.0533902	Foreign inside × 1906	-0.4713709	0.0656478
Foreign outside × 1907	-0.3250584	0.0586000	Foreign inside × 1907	-0.4455852	0.0524087
Foreign outside × 1908	-0.3828769	0.0531434	Foreign inside × 1908	-0.4996841	0.0489053
Foreign outside × 1909	-0.3589235	0.0504000	Foreign inside × 1909	-0.5122520	0.0393736
Foreign outside × 1910	-0.3014513	0.0557000	Foreign inside × 1910	-0.4170000	0.0451895
Foreign outside × 1911	-0.3810822	0.0604000	Foreign inside × 1911	-0.4423512	0.0438255
Foreign outside × 1912	-0.3504278	0.0725974	Foreign inside × 1912	-0.4614005	0.0469158
Foreign outside × 1913	-0.3969427	0.0618991	Foreign inside × 1913	-0.4774367	0.0406870
Foreign outside × 1914	-0.4324189	0.0729455	Foreign inside × 1914	-0.5041368	0.0570166
Foreign outside × 1915	-0.4933692	0.0494931	Foreign inside × 1915	-0.4917767	0.0444098
Foreign outside × 1916	-0.5697513	0.0519064	Foreign inside × 1916	-0.5884312	0.0404121
Foreign outside × 1917	-0.6764510	0.0456782	Foreign inside × 1917	-0.6599393	0.0421489
Foreign outside × 1918	-0.6963259	0.0432795	Foreign inside × 1918	-0.6351183	0.0385084
Foreign outside × 1919	-0.7146919	0.0456749	Foreign inside × 1919	-0.6565400	0.0445911
Foreign outside × 1920	-0.6643524	0.0453601	Foreign inside × 1920	-0.5991752	0.0425805
Foreign outside × 1921	-0.6157747	0.0557833	Foreign inside × 1921	-0.5824137	0.0427683
Foreign outside × 1922	-0.6090650	0.0473282	Foreign inside × 1922	-0.5619255	0.0361160
Foreign outside × 1923	-0.6149703	0.0423746	Foreign inside × 1923	-0.5576072	0.0292087
Foreign outside × 1924	-0.5398764	0.0569984	Foreign inside × 1924	-0.5262194	0.0435548
Foreign outside × 1925	-0.5421477	0.0475217	Foreign inside × 1925	-0.5030797	0.0353864
Foreign outside × 1926	-0.5306024	0.0517879	Foreign inside × 1926	-0.5029824	0.0307286
Foreign outside × 1927	-0.5707151	0.0478170	Foreign inside × 1927	-0.5446742	0.0344149
Foreign outside × 1928	-0.5513192	0.0404107	Foreign inside × 1928	-0.5238010	0.0296450
Foreign outside × 1929	-0.5332294	0.0472960	Foreign inside × 1929	-0.5003044	0.0342243
Foreign outside × 1930	-0.5496374	0.0429039	Foreign inside × 1930	-0.5057730	0.0350607
Paper FE			YES		
Observations			105,378		
Number of papers			35,126		

Notes: The Table reports parameter estimates of regression (2). "Foreign outside" measures the share of citations to research from outside the camp, relative to research from home. "Foreign inside" measures the share of citations to research from foreign authors inside the camp, relative to research from home. We focus on citations to recent research, i.e. research published in the preceding five years. For example, "Foreign outside × 1905" measures the relative share of citations to research from outside the camp published between 1901 and 1905. Similarly, "Foreign outside in 1906" measures the relative share of citations to research from outside the camp published between 1902 and 1906. Standard errors are clustered at the country-times-field level. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.6:
RELATIVE CITATIONS AS MEASURED BY CITATION SHARES: NEUTRALS

Dependent variable: *Neutral Cit. Sh. to recent work*	(1)	(2)	(3)	(4)
Foreign *outside* camp × Post 1914	-0.060	-0.074		
	(0.041)	(0.077)		
Allied camp × Post 1914			0.107**	0.010
			(0.052)	(0.068)
Central camp × Post 1914			-0.195***	-0.096
			(0.045)	(0.072)
Foreign *inside* camp × Post 1914	0.009	0.100*	0.009	0.100*
	(0.024)	(0.054)	(0.024)	(0.054)
Paper FE	YES	YES	YES	YES
Camp main effects	YES	YES	YES	YES
Camp-specific time trends		YES		YES
Observations	5,865	5,865	9,775	9,775
Number of citing papers	1,955	1,955	1,955	1,955
Within R-squared	0.528	0.528	0.206	0.209

Notes: The Table reports estimation results from four versions of regression (1) for Neutral citing papers published between 1905 and 1930. In columns (1) and (2) the dependent variable measures the share of citations to research produced by scientists based at home, foreign scientists inside the camp, and foreign scientists outside the camp. The dependent variable in columns (3) and (4) further splits the Neutral share of references to research from foreign scientists outside the camp into Allied, Central, and Other (not reported in the table). We focus on citations to recent research, i.e. research published in the preceding five years. The reference/omitted category is the Neutral citation share to research from home. Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from the *ISI - Web of Science* (see section 2 for details).

B Data Appendix

B.1 Further Details on the Censuses of University Scientists for 1900 and 1914

As described in the main text, we digitized two historical censuses of all university scientists in the world from the 1900 and 1914 volumes of *Minerva–Handbuch der Gelehrten Welt*. Because the formatting of early volumes of *Minerva* makes the use of Optical Character Recognition software infeasible, all names and specializations were typed in by hand with the help of research assistants. The data list 569 universities in the year 1900 and 973 universities in the year 1914 (Appendix Table A.1, panel (a)). Across all fields, the data contain 24,166 professors in 1900 and 42,226 professors in 1914.[31] A few universities, mostly smaller and less well-known institutions, only reported the number of professors but not their names. The data therefore contain names of 23,917 professors in 1900 and 36,777 professors in 1914 (Appendix Table A.1, panel (a)). In the five scientific fields we study in our analysis, the data contain 10,133 scientists in 1900 and 15,891 scientists in 1914 (Appendix Table A.1, panel (b)).

B.2 Further Details on Assigning Countries to Citing Papers and References

As described in the main text, we assigned countries to authors and references in a three step hierarchical process. First, we used the country information from the affiliation reported in papers that listed affiliations. Second, we used the country information from the two scientist censuses. Third, we expanded the country information for authors with identical names within the corresponding cited or citing journal.

In the second step of our country assignment, we matched the country information of the scientist censuses to the *Web of Science* publication data. To maximize the quality of this match, we matched on the last name, the initials, and the research field in a two-step process. First, we matched on last name, all initials, and research field; second, we matched previously unmatched papers on the basis of last name, first initial, and research field. Some scientists reported up to three research fields in the scientist census data, e.g. biology and medicine. Some journals in the *Web of Science* also published research from multiple fields. We mapped scientist fields into journal fields as follows:

[31] We use the term professor to refer to individuals who were the equivalent of assistant professors, associate professors, or full professors. We thank Clément de Chaisemartin, Henrik Kleven, Katrine Loken, Ioana Marinescu, Sharun Mukand, and Matti Sarvimäki for help with classifying university positions in various countries.

Table B.1: Mapping Journal Fields to Scientist Fields

Journal field	Journal Example	Scientists with the following fields are matched to papers in respective journals
Medicine	Lancet	Medicine
Medicine/Biology	Pflugers Archiv fur die Gesamte Physiologie des Menschen und der Tiere	Medicine, Biology
Medicine/Biology/Chemistry	Archiv fur Experimentelle Pathologie und Pharmakologie	Medicine, Biology, Chemistry
Medicine/Chemistry	Journal of Pharmacology And Experimental Therapeutics	Medicine, Chemistry
Biology	Annals of Applied Biology	Biology
Biochemistry	Biochemical Journal	Biology, Chemistry
Chemistry	Angewandte Chemie	Chemistry
Physical Chemistry	Journal of Physical Chemistry	Chemistry, Physics
Physics	Physical Review	Physics
Mathematical Physics	Sitzungsberichte der Preussischen Akademie Physikalisch-Mathematische Klasse	Physics, Mathematics
Mathematics	Acta Mathematica	Mathematics
General Science	Nature	Medicine, Biology, Chemistry, Mathematics

If a scientist only listed one research field in the scientist census data, e.g. physics, we matched him to all articles in journals that published some research in physics, i.e. physics, general science, mathematical physics, and physical chemistry. Scientists with multiple fields in the scientist census data, e.g. mathematics and physics, were matched to all articles that published some research in mathematics or physics.

The match was done hierarchically. First, we matched authors in the *Web of Science* data to the scientists from the 1914 census, as 1914 is in the middle of our sample period. Authors who did not merge with the 1914 census were matched to the 1900 census.

B.3 Further Details on the Nobel Nomination Data

As described in the main text, we collected data on all nominees for the Nobel Prize from Nobelprize.org (2014). The data contain 993 individuals who were nominated for a Nobel Prize for the first time between 1905 and 1945. To identify winners and the period when winners worked on their Nobel prize winning research, we merged these data with the data on Nobel Prize winners from Jones and Weinberg (2011).

We determined the main nomination field (physics, chemistry, or medicine/physiology) of each nominee by counting the number of nominations in each field. The main nomination field is the field for which a candidate obtained most nominations. E.g. if a scientist received five nominations in physics and one in chemistry, we defined his main nomination field as physics.

We then merged the nominees to all papers in our list of 161 journals from the *ISI Web of Science* for the publication years 1900 to 1940. To improve the quality of this match, and to reduce the probability of false positives, we only matched publications in journal fields that corresponded to likely publication patterns of scientists in certain fields. E.g. we only matched publications in physics, general science, mathematical physics, physical chemistry, and chemistry to individuals who received the majority of their nominations for the physics prize.

For six nominees, the last name and the initials of the first name were not unique, e.g. both "Paul Weiss" and "Pierre Weiss" were nominated for a prize between 1905 and 1945. To minimize the probability of false positives, we did not match these individuals if they worked in the same field.

Three of the six, however, worked in different fields, e.g. "Paul Weiss" was predominately nominated for the medicine prize and "Pierre Weiss" was predominately nominated for the physics prize. We matched these three scientists to a very strict definition of journal fields. E.g. we only matched them to physics journals (but not general science and other journals if they were physicists).

C The Quality of References and the Probability of Becoming a Hit Paper

The data for Figure 1 were collected from the *ISI Web of Science* and *Minerva.* For the construction of this figure, we focused on the papers that were part of our main estimation sample for normal scientific times, 1905-1913 and 1926-1930, 22,562 papers overall.

We measure whether a reference is in the top 1%, top 3% or top 5% using the field-level citation distribution of all papers in the 161 journals in the *Web of Science* data, independently of whether the paper ended up in our sample of papers with county information on authors and references.

For Figure 1 we define a "hit paper" as a paper that ended up in the field-level top 1 percent of the citation distribution in our sample of papers. Alternatively, we could also define "hit papers" using the field-level citation distribution of all papers in the 161 journals in the *Web of Science* data. The results are very similar (see Appendix Figure A.1). With this alternative definition of a hit paper, more papers achieve "hit status" because we are more likely to know the country of authors and references for more established, and better, authors (they are more likely to have a university position).

D Data on Journal Delays

We collected data on entry stamps from the Harvard library for four international journals. Two Central journals, the *Zeitschrift für Analytische Chemie* and the *Annalen der Physik*, and two Allied journals, the British journal *Nature*, and the French journal *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences.* Appendix Table D.1, column (2), reports the volumes and issues for which we obtained entry stamps from the Harvard library. Sometimes two issues within a volume were published at the same time (e.g. no. 3 and 4) and hence they only have one entry stamp and one publication date. In very rare cases, the entry stamp is so blurred that the entry date is not legible.

At Harvard, we collect 61 (legible) entry stamps for the *Zeitschrift für Analytische Chemie*, 145 for the *Annalen der Physik*, 161 for *Nature*, and 28 for the *Comptes Rendus.*

Table D.1: Data Sources Journal Delays

(1) Year reported in Figure (2)	(2) Volume(s) at Harvard	(3) Issues with stamps at Harvard	(4) Issues with stamp at Heidelberg	(5) Publication Dates
Panel (a): Zeitschrift für Analytische Chemie				
1910	49	all		10/27/1909 to 10/15/1910
1913	52	all		10/30/1912 to 09/17/1913
1917	56	all		11/30/1916 to 01/05/1918
1919	58	all		01/20/1919 to 01/22/1920
1921	60	all		12/15/1920 to 10/06/1921
1923	62	all		09/30/1922 to 05/20/1923
1927	71	all		04/14/1927 to 08/23/1927
Panel (b): Annalen der Physik				
1910	31-33	all	33:1	12/30/1909 to 12/20/1910
1913	40-42	all	40:1, 41:1, 42:1	12/31/1912 to 12/23/1913
1917	52-54	all	52:1, 53:1, 54:1	02/15/1917 to 04/26/1918
1919	58-60	all		01/17/1919 to 12/19/1919
1921	64-66	all	64:1-2, 65:1, 66:1	01/20/1921 to 12/20/1921
1923	70-72	all	70:1, 71:1, 72:1	01/18/1923 to 11/??/1923
1927	82-84	all	82:1, 83:1, 84:1	12/16/1926 to 01/13/1928
Panel (c): Nature				
1910	83	all		03/03/1910 to 06/30/1910
1913	91	all		03/06/1913 to 08/28/1913
1917	99	all		03/01/1917 to 08/30/1917
1919	103	all		03/06/1919 to 08/28/1919
1921	107	all		03/03/1921 to 08/25/1921
1923	111	all		01/06/1923 to 06/30/1923
1927	119	all		01/01/1927 to 03/26/1927
Panel (d): Comptes Rendus				
1910	150-151	1, 23, 10, 21		01/03/1910 to 11/21/1910
1913	156-157	7, 23, 8, 21		02/17/1913 to 11/24/1913
1917	164-165	7, 22, 8, 25		02/12/1917 to 12/17/1917
1919	168-169	3, 14, 26, 18		01/20/1919 to 11/03/1919
1921	172-173	2, 23, 15, 24		01/10/1921 to 12/12/1921
1923	176-177	10, 4, 19, 25		03/05/1923 to 12/17/1923
1927	184-185	7, 23, 7, 23		02/14/1927 to 12/05/1927

Notes: The Table reports volumes, issues, and publication dates for four international scientific journals. The *Annalen der Physik* only reported the month of publication for the last two issues published in 1923. For the results reported in the paper we set the publication dates to the mid of the month for those two issues. The data were collected by the authors from the Harvard Library and the Library of the University of Heidelberg.

Depending on the journal and issue, either the publication date or editorial deadline is reported for each issue. The *Zeitschrift für Analytische Chemie* always reports editorial deadlines, the *Annalen der Physik* reports publication dates until 1923 and editorial deadlines in 1927, and *Nature* and the *Comptes Rendus* always reports publication dates. To make entry dates comparable across journals and over time, we assumed that editorial deadlines were 14 days before the publication date of the journal.

We calculate average arrival delays as the difference between arrival date (as measured by the entry stamp) and the publication date and average these delays for each year (1910, 1913, 1917, 1919, 1921, 1923, 1927) and journal.

Because of the way that journals were bound at Heidelberg, entry stamps are only preserved for the first issue of each volume for the *Annalen der Physik* at Heidelberg (see Appendix Table D.1, column (4)). When we report differences between arrival delays for the *Annalen der Physik* at Harvard and Heidelberg, we only use issue numbers that were available in both libraries.

E Further Details on the ICM Proceedings, 1897-1932

We collected data on the number of delegates at all *International Congresses of Mathematicians* (ICMs) from 1897 until 1932 from historical volumes of the ICM Proceedings, available at http://www.math-union.org/home/. After each congress, the local organizers edited one or more volumes of ICM Proceedings summarizing the main information regarding the conference. The historical ICM Proceedings were written in the official language of the host country, e.g., German for the 1904 ICM held in Heidelberg and Italian for the 1908 ICM held in Rome. Among other information, the volumes report the full list of participants at each congress. This list contains the professional address of each participant. From this address, we obtained the number of delegates by countries reported in Table 2.

F Further Details on the Solvay Conferences in Physics

We collected data on the participants of every *Solvay Conference* in Physics from 1911 (first edition) until 1930 from Mehra (1975). For each conference, Mehra (1975) reports a historic picture of the participants during the event with the corresponding names and professional addresses (at the moment of the event). We used this information on the country for Figure 3 and Appendix Table A.2. Note that in some of the historic pictures in Figure 3, only a subset of all conference participants appear.