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Prizes for Basic Research –
Human Capital, Economic Might and the Shadow of History[*]

Abstract

This paper studies the impact of global factors on patterns of basic research across countries and time. We rely on the records of major scientific awards, and on data dealing with global economic and historical trends. Specifically, we investigate the degree to which scale or threshold effects account for countries share of major prizes [Nobel, Fields, Kyoto and Wolf]. We construct a stylized model, predicting that lagged relative GDP of a country relative to the GDP of all countries engaging in basic research is an important explanatory variable of country's share of prizes. Scale effects imply that the association between the GDP share of a country and its prize share tends to be logistic -- above a threshold, there is a "take off" range, where the prize share increases at an accelerating rate with the relative GDP share of the country, until it reaches "maturity" stage. Our empirical analysis confirms the importance of lagged relative GDP in accounting for countries' prize shares, and the presence of "winner takes all" scale effect benefiting the leader. Using measures of casualties during the wars, we find that the only significant effect can be found for a lag of 3 decades – i.e., deaths in the war negatively impact the viability of basic research about 30 years after the fact. With more recent data, we document the growing importance of countries that used to be at the periphery of global research, possibly advancing towards the take off stage.

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This paper studies the impact of global factors on patterns of basic research across countries and time. Understanding creativity and path breaking scientific research remains a black box. Short of having detailed information on networks of scientific research, and the effort associated with these networks, we rely on the records of major scientific awards, and on data dealing with global economic and historical trends. Specifically, the cumulative record of major prizes includes more than a hundred years of Nobel laureates in Chemistry, Medicine and Physics; as well as the shorter but significant record of the Fields Medal, Kyoto and Wolf prizes for basic research. We use this information to study the degree to which scale or threshold effects account for countries share of major prizes.

Related questions were investigated in the context of economic development. For example, an intriguing study by Davis and Weinstein (2002 and 2004) inquired into the distribution of economic activity within Japan over the long run, finding that even very large temporary shocks to urban areas have no long-run impact on city size. They examine this question in the context of the intense Allied bombing of Japanese cities and industries in WWII, finding that in the aftermath of even immense shocks, a city typically recovers not only its population and its share of aggregate manufacturing, but even the composition of specific industries it had before. Hence, they do not find support for path dependency, which frequently has been linked to returns to scale [see Krugman (1991) and David (2000)]. To the best of our knowledge, little research was done on these questions in the context of basic scientific research. The immense global shocks of the 20th century provide the background to our investigation, asking questions akin to Davis and Weinstein: the degree to which economic might and World Wars have affected basic scientific research in enduring ways. We also use the combined data of major prizes to gauge the emergence of new trends.

To grasp the issues involved, Figure 1A plots the decade averages of shares of Nobel prizes for science (Chemistry, Medicine and Physics) during the 20th century, where the time unit is five year segments starting from 1900-1904. The most dramatic development, apparent in this figure, has been the take off of the U.S. share, starting from 0%, and reaching about 70% by the end of the century. Figure 2 plots the U.S. GDP as share of total GDP of all countries for which at least 10 science Nobel prizes were awarded from 1900 to 2005, and the U.S. share of Nobel prizes for sciences, where GDP share is lagged by two decades (reflecting the average gap between timing of research and the awarded prizes). The fitted line in figure 2 is a third order polynomial. The figures suggest that the U.S. take off has been closely linked to the sizable increase in the U.S. GDP share, as well as the decline in the share of Germany. The purpose of our paper is to look systematically at the factors accounting for these dramatic changes, putting it in the context of a model that provides possible links between relative GDPs and prize shares, in the presence of scale effects associated with scientific research.

Figure 2 suggests that the association between GDP and Prize shares is logistic. This observation is consistent with the predictions of a stylized model described in the next section, explaining countries prize share in the presence of scale effects associated with basic research. Specifically, the model predicts that lagged relative GDP of a country relative to the GDP of other countries engaging in basic research is an important explanatory variable of country's share of prize. Scale effects imply that the association between the GDP share of a country and its prize share tends to be logistic -- above a threshold; there is a "take off" range, where the prize share increases at an accelerating rate with the relative GDP share of a country, until it reaches a "maturity" stage.

Simulating a simple version of our model suggests that it fits well the first part of the U.S. basic research take-off, but under-predicts its speed [see Figure 5]. This observation follows an intriguing discontinuity of the U.S. basic research take-off: the U.S. prize shares were either below 15% during most of the first third of the 20th century, or well above 40% after 1940. Our empirical analysis confirms the importance of lagged relative GDP in accounting countries' prize shares, and the presence of "winner takes All" scale effect. The "winner takes all" effect may be further reinforced by immigration patterns: from 1936 onward, 73 of U.S. Nobel laureates were awarded to immigrants from other countries, amounting to 18.2% of the total Nobel prizes in basic research awarded to *all* countries from 1936. The corresponding Nobel awards gained through immigration by other major recipient countries are 15 for the UK, 12 for Switzerland, and only 4 for Germany (see table 1A). During that time, 26 Nobel prizes were German immigrants, 8 Nobel foreign laureates were born in Austria, 7 in the UK, 7 in Canada, 6 in Hungary, 5 in Poland, and 4 in Russia (see Table 1B for more details).[1] Our analysis is consistent with the notion that the World Wars set in motion forces that hasten the U.S. take-off, and suggests that immigration patterns accelerated this process.

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[1] Hence, the "net immigration" of Nobel laureates from 1936 has been 73 to the US, 12 for Switzerland, 8 for the UK, - 1 for France, - 4 for Russia, -5 for Poland, - 5 for China, -6 for Hungary, - 7 for Canada, - 8 for Austria, - 21 for Germany.

A by-product of our analysis is that, *ceteris paribus*, the return toward a more symmetric configuration among leading industrial countries will reverse overtime some of the trends observed during the 20th century. A glimpse into this possibility is provided in Figure 1B, plotting the combined prize share of all countries minus Europe and the U.S., referred as AOC (All Other Countries). In reading this figure, one should keep in mind the two decade average lag between the actual research, and the awarded research. Figure 1B suggests two instances of impending AOC takeoffs during the last 70 years; the first is 1940-1960 (reflecting research done, on average, during 1920-1940), and 1990-2005 (reflecting research done during 1970-1985). The first takeoff was apparently aborted due the upheaval associated with the WWII. These trends are further reinforced by looking of the aggregation of the Nobel with the other prizes for basic research (see Figure 1B).

In our concluding remarks we outline important issues that are not dealt with in the present paper, like the role of the public versus private funding of basic research, quality of governance, the changing roles of research networks and the diffusion of information technology, etc. Section 1 outlines a stylized model explaining key determinants of basic research — the detailed model is in Appendix A. Section 2 discusses the data used in the paper. Section 3 summarizes the empirical regularities and the results of regressions explaining the changing prize shares of various countries. Section 4 concludes.

1. Stylized model of key determinants of basic research.

This section outlines a stylized model, used to identify possible variables applied in our empirical study. Awarding prizes to basic research is the outcome of a periodic contest among the stock of major recent contributions. The definition of "recent" is bounded by scholars' life expectancy since prizes are not awarded posthumously. The inter-temporal importance of major contributions is determined by the speed of diffusion of knowledge. As we do not have a tractable way of comparing the relative importance of the major contributions, we adopt a simple threshold approach: all major scientific contributions vintage of the same period are treated as equal candidates for wining the prize contest. The arrival rate of major contributions in a country depends on the knowledge in the country, potentially interacted with the 'global stock' of knowledge in non linear ways due to scale and networking effects. Such knowledge is dubbed in economics as “human capital,” evolving over time as the outcome of investment, adjusted for depreciation caused by aging, calamities like wars, etc.[2] The investment in human capital depends positively on the scale of the economy that supports the research, like the real GDP, real GDP pre capita, etc.

A key aspect of scientific research is the presence of returns to scale, possibly due to fixed costs and networking effects. Specifically, basic research may lack immediate commercial use, yet it is associated with significant fixed and set-up costs (costs of setting laboratory, running experiments, etc…). These costs may be prohibitive enough to be supported only by few rich countries, in few well endowed centers. Hence, one expects that these centers will be a magnet for scientific work, leading to scale economics and agglomeration (see CERN in Switzerland,[3] or the Brookhaven national laboratory in the U.S.[4]). Furthermore, research benefits frequently from peer interaction, leading to network externalities, where doubling the number of scholars in the network may more than double the productivity of the network.[5] These considerations suggest that doubling the investment in knowledge more than double the efficacy of research. Further magnification of these effects occurs when scholars are mobile; implying that research centers located in countries that are friendlier to immigrants would be attractors of talent, ending up as key research hubs. Conversely, research hubs may be destroyed rapidly if tolerance towards immigrants diminishes, or if calamities reduce the resources available to basic research, as has been vividly illustrated in the first half of the 20th century.

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[2] Human capital is the stock of expertise, knowledge and skill, embodied in an individual as a result of education, training, and experience, that makes them more productive [see Becker (1975) for conceptualizing and measuring human capital].

[3] CERN (French for *European Nuclear Research Centre*) is located near Geneva. Its recent purchase of Europe's flagship particle accelerator (LHC) has been associated with capital costs of more than $ 2 B. A *Why Geneva* Web page credits the proximity of CERN to making Geneva a research hub: “*Many of the no fewer than 44 Nobel prizes awarded to residents of Geneva came as a result of the presence of CERN in the city*” (see http://www.geneva.ch/f/lhc.htm). The presence of prize winning immigrants is also evident in our table 1A and 1B.

[4] Established in 1947 on Long Island, Upton, New York, Brookhaven is a multi-program national laboratory operated by Brookhaven Science Associates for the U.S. Department of Energy (DOE). Six Nobel Prizes have been awarded for discoveries made at the Lab. Brookhaven has a staff of approximately 3,000 scientists, engineers, technicians and support staff and over 4,000 guest researchers annually (see http://www.bnl.gov/world/).

[5] Network externalities refer to the effects on a user of a service of others using the same services. Positive network externalities exist if the benefits are an increasing function of the number of other users. For example, a network connecting n scholars entails potential 0.5n(n-1) pair interactions. If the productivity of the network depends linearly on pair interactions, doubling the network would almost quadruple network’s productivity. This effect is further magnified if, as is frequently the case, basic experimental research needs a sizable crew of scholars, well above pair interactions.

The focus of our study is on the degree to which macroeconomic variables, interacted with history, explain the cross country distribution of basic research, quantified by the countries' share of Nobel and other major scientific prizes. We concentrate on countries that have reached the threshold level of development needed to afford meaningful investment in basic research, and refrain from modeling the micro details of the network effects associated with scientific research. We consider a stylistic model, where scale effects may imply that the arrival rate of scientific contributions depends in a non linear manner on human capital. The human capital of the country follows a simple accumulation rule, where a fraction of the real GDP is invested into forming future human capital.

The details of the model are provided in the Appendix. To illustrate some of its predictions, it's handy to consider a simple case. Suppose that all countries doing basic research are aggregated into 2 blocks, say the USA and All Other Countries (AOC) that are part of the research frontier. To simplify further, assume that the OAC block is composed of n symmetric countries, and define the unit of time (= a period) to cover a generation of scientists (say 25 years). Suppose further that all the countries engaging in basic research differ only in their scale, having the same productivity and accumulation parameters. These assumptions allow us to solve the prize share of the U.S. as a function of the lagged real U.S. GDP relative to all other countries GDP.

Figure 3a illustrates the solution, plotting the U.S. share of the prizes predicted by our model as a function of the relative GDP share of the U.S./AOC. The bold curve corresponds to the benchmark case of two countries (the USA and AOC), the absence of foreign human capital externality (i.e., only domestic human capital contributes to the scientific contributions of the country), and significant scale effects. The solid curve to the left of the bold plots the case where AOC are composed of two symmetric countries (keeping all other assumptions). Note that more fractured composition of AOC reduces the research effectiveness there, increasing thereby USA share. The dotted curve modifies the benchmark by allowing modest human capital externality, where foreign human capital impact domestic research by 5%. Human capital externality increases the share of the smaller block, at the expense of the larger block. Figure 3b plots the same curves in the absence of returns to scale in research. Removing scale effects considerably mitigates the prize share of the larger block (increasing thereby the share of the smaller block). It also implies simple additivity of the countries composing the AOC block, and eliminates the inflection point.

The association between the relative GDP shares and the prize share in the presence of scale effects resembles a logistic curve. The appendix shows that greater scale effects implies higher threshold of relative GDP is needed in order to reach the "taking off" range associated with the accelerating increase in the prize share. Once this range has been reached, the takeoff is faster. This result is illustrated in Figure 4a, focusing on the case where the scale effect is magnified from 2 [the bold curve] to 4 [the solid curve], drawn for the case where AOC is composed of a unique country. Figure 4b replicate this exercise for the case where the AOC is fractured into two symmetric countries. As one may expect, it implies that the U.S. takes off at a lower relative share. Figure 5 add to the U.S. Nobel shares / lagged U.S. share of World GDP during the 20th centaury the share corresponding to a simulated version of the stylistic model. While the model is capturing well the first part of the take off, it underestimate the speed of reaching the "mature stage" of the U.S. Our empirical work suggests that some of the fast take off of the U.S. may be accounted by the effects of the two World Wars, disrupting research networks in favor of the U.S.[6]

The above model offers several predictions, some summarized below:

- Lagged relative GDP of a country relative to the GDP of other countries engaging in basic research is an important explanatory variable of country's share of prize.
- Scale effects imply that above a threshold, there is a "take off" range, where the prize share increases at accelerating rate with the relative GDP share of a country, until it reaches "maturity" stage.
- A more fractured AOC block reduces in the presence of scale effects the relative GDP needed to induce a prizes share "take off".
- Greater fluidity of the flow of information and scholars across countries (possibly due to the proliferation of IT technology and the drop of airfares) increases the externality associated with foreign human capital, mitigating thereby the advantages of the large block induced by scale effects.

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[6] Other obvious shortcomings are that our simulation assumes the key parameters [the scale effects, number of countries engaged in basic research, etc.] have been constant during the 20th centaury, and the imposed equal productivity of all the relevant countries.

2. Data

Our data is generally taken from two sources. Data on prizes is obtained from the official websites of the respective prizes. When the relevant biographical data was not available in the prize's website, we obtained additional information from other on-line sources. All the macroeconomic data is taken from *The World Economy: Historical Statistics CD-ROM* based on data compiled by Maddison (2003).

For the Nobel prizes, we note the country in which each recipient resided at the time of the award. We also record the country location and the decade in which the research for which the award was given was conducted – this data is obtained by reading the narrative biographical description of each awardee. In case no description was provided (as for some of the early Nobel awards) we obtained this data from other sources. We start from the first Nobel awards presented in 1901 and do not record the Economics, Peace and Literature awards. Our sample covers 509 Nobel prizes awarded in Chemistry, Medicine and Physics during 1901-2005.

We record the same variables for the Wolf Prize, given annually in agriculture, chemistry, mathematics, medicine and physics since 1978 [199 Wolf Prizes]; the Kyoto Prize, given annually in advanced technology and basic sciences since 1985 [47 awarded]; and the Fields Medal, given every four years in mathematics since 1936 [44 awarded].

We construct two separate panel data-sets. The first includes five-year totals for prizes awarded, per country-5 years observation. In this dataset, each prize is recorded for the year in which it was awarded and the location of the researcher/s at the time of the award. In the second data set, we compile a panel of country-decade observations in which each prize award is recorded for the time in which the most important awarded research was done and at the location in which that research took place.

Hence, a prize awarded for research done in Germany but awarded to a scientist who was residing in the UK 20 years later at the time of the award, will, for the 5-years dataset, be counted for the UK at the time of the award. For the 10-years dataset, the prize would be credited to Germany 20 years before the award.[7]

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[7] This implies that with our 10-years dataset, we are controlling for the effect of immigration (see the discussion on the importance of immigration in the introduction to this paper). Since results for the two datasets are very similar, we argue that while immigration is important, it cannot be the only reason for the US scale effect we observe.

Since for many of the smaller countries, very few awards were given during this past century, we record this data in 10 separate country groups: the United States, the United Kingdom, Germany, France, Scandinavia, other European countries, Australia & Canada, Japan, the USSR (and later Russia), and all other countries (these include those countries that received at least one prize).[8] Correlations between the different prize measures is provided in appendix B.

For the macroeconomic data, we use GDP (in constant 1990 international dollars), and population measures taken from Maddison (2003). These measured are averaged over 5(10) years for the 5(10) years data panels. To measure the WWI and WWII casualties, we obtain data on war deaths (both civilian and military) and divide those by the population in each country. The WWI casualties are attributed to 1916-1920, or 1911-1920 in the cases of the 5- and 10-years datasets, respectively. Appendix B details data sources and descriptive statistics.

3. Empirical results

We stipulate an empirical model that is based on equation (A4) of the theoretical model we developed in the Appendix. Since we are interested in the amount of generated basic research, as proxied by the amount of prizes won, we stipulate a benchmark model in which the share of each country's prizes (out of the total global amount) depends on a country's income (GDP) and its population. Since GDP per capita might be the relevant income measure to approximate the amount of resources available for domestic R&D investment, we speculate that the population variable might have a negative coefficient.

Since the construction of the LHS variable (prize share) is censored on the left by zero, we estimate a standard Tobit, estimated by maximum likelihood. The model we estimate is the following:

$$(1) \qquad \frac{P_{it}}{P_W} = \begin{cases} T_{it} = \alpha\frac{N_{it}}{N_W} + \beta_1\frac{Y_{it}}{Y_W} + \beta_2[\frac{Y_{it}}{Y_W}]^2 + \gamma D_{it} + \varepsilon_{it} & if \quad T_{it} > 0 \\ 0 & if \quad T_{it} \leq 0 \end{cases}$$

where $P_{it}; N_{it}; Y_{it}; P_W; N_W; Y_W$ are the total prizes (*P*) credited to research done in country *i* during period *t (t* is typically two decades earlier than the time the prize was awarded), the population (*N*) and gross domestic product (*Y*) for country *i* and time *t*, or for the total world (*W*) where the

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[8] Our sample covers 509 Nobel prizes awarded in Chemistry, Medicine and Physics during 1901-2005. The "All Other Countries" group received only 9 Nobel prizes, less than 2% of the total awarded. This observation is consistent with the presence of strong scale effects discussed above.

world is defined as all those countries which have won prizes. In a number of specifications we also include binary variables (D_{it}) or a measure of casualties from the two World Wars per country panel observation. For the error term, we assume $\varepsilon_{it} \sim N[0, \sigma^2]$.

In table 2, we report the results of our benchmark specification, in which we examine the impact of GDP and population on the incidence of prizes. Table 2A employs the 10-years panel in which each prize is registers at the time of the research for which the award was given. We observe an average lag of two decades between the time of research and the award. We also estimate the same specifications for the 5-years panel in which each prize is registered at the time of the award. Because of the observed lag between research and award, in table 2B, we lag the independent variables by 4 lags (20 years) for this dataset. We confirm the need to lag the independent macro variables by estimating specifications for different lag structures and observing that the optimal lag is indeed 20 years.[9]

Results in columns 1-3 (tables 2A and 2B) demonstrate that the incidence of Nobel winnings is clearly positively associated with GDP and negatively associated with population (after controlling for GDP). Results in columns 4-6 (tables 2A and 2B) confirm the same associations with a different dependent variable: The total number of prizes (Nobel, Fields, Kyoto and Wolf) awarded for each country-period as a share of the total awards for that period.

In table 3, we present the complete specifications examining the importance of scale effects; repeating the same specifications for the 10-years and 5-years panels. Since results are qualitatively the same, we focus on the 10-years panel presented in table 3A. In column 1, we add to our benchmark specification the square of GDP. The coefficient is statistically significant at the 99% confidence level suggesting a clear incidence of scale effects.[10] In column 2, we employ, instead, binary variables that examine whether Germany before WWII and the U.S. after WWII are unique in the level of their exposure to prizes. We further speculate that, at least for the Nobel prize, there might be a home-team bias and therefore include a binary variable for Scandinavia. Pre-WWII Germany and post-WWII U.S. are clearly unique cases (with their

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[9] We estimate the model with a variety of lag structures and in all cases the only coefficient that comes out significant is the (*t-4*) one – implying a lag of two decades. Results are available from the authors upon request.

[10] This finding contrasts with a recent work, Rose (2006), that failed to find scale effects in: “the level of income, inflation, material well-being, health, education, the quality of a country’s institutions, heterogeneity, and a number of different international indices and rankings.”

coefficients significant at the 1% level). We find no evidence of home-team bias and discard this variable in all subsequent estimations.

In column 3 (tables 3A and 3B) we add to the $(GDP)^2$ variable the dummy for post-WWII U.S. Since the coefficient on $(GDP)^2$ is not significant once the U.S. post-WWII dummy is included, we conclude that the dynamic scale effects we obtained are completely driven by the impact of the U.S. presence in this competition on prizes. This is also evidenced by the fact that our fit measures are not improved when $(GDP)^2$ is included in the specification (compare columns 2 and 3 (tables 3A and 3B). These results carry thorough once we use, as our dependent variable in columns 4-6 of tables 3A and 3B, the country share of total prizes (instead of the country share in Nobel prizes).

In table 4, we investigate whether our results are driven by the destruction of WWII and not by the U.S.-dominated scale effects we observed. Using our measure of casualties during the war, we investigate it's lag structure in columns 1-3. We find that the only significant effect can be found for a lag of 3 decades – i.e., deaths in the war negatively impact the viability of basic research about 30 years after the fact. This result, though, is not very robust. In columns 4-5 (table 4), we examine whether the WWII destruction effect cannot be accounted for by the non-linear changes in incomes or just by the rising post war dominance of the U.S. We find both of these hypotheses to be confirmed and conclude, not unlike Davis and Weinstein (2002 and 2004), that the World Wars' destruction did not have a long-term statistically observable effect on the production of basic research. Once again, we confirm, in column 5, that the post-War U.S. prominence in basic research dominates the scale effect.

Since we observed the increase in the share of prizes going to previously peripheral countries in the last two decades, we postulated that it is possible that the structure of the relationships we identified has recently changed. In table 5 column 1, we run the same specification as in table 3B column 1, but restrict our dataset to 1975-2004. We find no evidence of such change with results corresponding closely to the results obtained from the full dataset.

Another interesting question is whether we can identify scale effects in the non-leading countries as well. In table 5 column 2, we re-run the specification in table 3B column 1 but exclude from our dataset the U.S. observations. Interestingly, the GDP^2 variable is no longer significant; this leads us to conclude that the scale effect we observed is indeed probably unique to the leader.

Figure 7a reports the Nobel Prize shares of the US in two distinct ways. The shaded curve, award time, reports the average Nobel share awarded to US residents per decade during the 20th century (it is obtained from the five year panel described in data section). The solid curve, real research time, reports the research share done in the US during the actual decade of the work credited later with the Nobel Prize, 1880s-1970s (it is obtained from the ten year panel described in the data section). The difference between the two curves reflects the delay between the actual research and the Nobel award, and the impact of scholars' mobility. The solid curve indicates that US basic research take-off, measured in real research time, started during 1920s-1930s, reaching the maturity stage during 1940s-1970s. Comparing the two curves in Figure 7a suggests that the first stage of the US take-off occurred prior to the immigration of talent propagated by the World Wars. This immigration contributed to the speed and the intensity of US take-off. Figure 7b reports the Nobel prizes shares for Germany applying similar methodology. It shows vividly Germany's basic research leadership during the 1890s-1920s, abruptly losing it during the 1930s. Comparing the two curves in Figure 7b reveals that the bulk of the actual basic research done in Germany during the 1920s was credited to other countries, as is suggested by the immigration patterns summarized in Table 1. The 1930s was the watershed decade, where the US emerged as the undisputed basic research leader. Both 7a and 7b implies that the World Wars set in motion forces that hasten the U.S. take-off, and suggests that immigration patterns accelerated this process.

4. Concluding remarks

Our empirical analysis confirms the importance of lagged relative GDP in accounting prize shares, and the presence of "winner takes all" scale effect. The relative GDP variable accounts for the prize shares of the non-leading countries, yet it falls short in accounting the scale effects impacting the leading country. Intriguing observations dominating the patterns of basic research in the last hundred years are the leadership role of Germany during the first third of the 20th century; and the rapid U.S. take-off during the 1930s, solidifying the U.S. basic research leadership position shortly after. Our analysis is consistent with the notion that the World Wars set in motion forces that hasten the U.S. take-off, and suggests that immigration patterns accelerated this process.

We close the paper with several concluding remarks and a discussion of some open issues left for future research. This work has investigated the process of producing basic research. We have not examined the links between successful basic research and private investment and corporate sector's profitability and other possible social benefits. After all, basic research is rarely the end target and the economic literature has suggested a number of goals. These issues have been examined before but no consensus has yet emerged from this literature (for a recent survey, see Salter and Martin, 2001). Some of these questions might be related to our own research on the preliminary stages of basic research since one expects that it would be easier to fund basic research in countries with deeper spillover from basic research to private (or public) rents.

The interplay between the private and the public sector in promoting basic research deserves more investigation. The basic research take-off of the U.S. happened during the first half of the 20th century, a time where the involvement of public funding in basic research was limited. The solidification of the role of the U.S. as a hub of basic research happened during the second half of the 20th centaury, a time of greater involvement of the public sector in funding or directing basic research. This observation is validated in Figure 6, where the solid curve depicts the constant dollar involvement of the U.S. government in funding basic research by various sectors.[11] Obtaining more detailed information about the private versus public funding of basic research in various countries could potentially enable researchers to identify the role of public funding in the take-off process.

Besides the public-private funding issue, other factors might also lead to differing magnitudes of the scale effects in basic research across countries and time. In-depth studies of the role of research networks possibly using empirical methodology similar to the Erdös number project might shed some light on these questions.

The recent diffusion of information technology has led to cheaper means of communication, and reduced the coordination costs of conducting joint research across geographical distance. The presence of these new technologies increases the spillovers from foreign to domestic research, as well as the possibility of greater cross-country collaborations. Whether the telecommunication

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[11] The point is exemplified by the growing role of NSF, NIH, NASA [see Science and Engineering Indicators (2006)]; and is reinforced by the time lag between the actual research and the timing of awards. The NSF was established by the National Science Foundation Act of 1950. The NIH grew out from the Laboratory of Hygiene and was reorganized in 1930 by the Ransdell Act into the National Institutes of Health. NASA was established in 1958.

revolution indeed changed the calculus of conducting basic research remains a challenge for future work.

In closing the paper, we would like to emphasize the inability of this kind of econometric inference to prove causality, and the limited predictive ability of correlations without the luxury of conducting controlled experiments—see Lucas's (1976) critique of econometric policy evaluation. This is especially true in circumstances such as our case dealing with the black box process associated with creativity. An obvious implication of our study is that, in the presence of scale effects, a critical size is a necessary condition for basic research take-off. While the evidence in this paper is consistent with the growing research importance of countries that used to be at the periphery of global research, it is a mistake to equate economic take-off with basic research take-off, as it may confuse necessary and sufficient conditions. A loose interpretation of the U.S. experience is that the growing allegiance of public and private resources helped in solidifying and speeding the basic research take-off. Yet, a growing body of economic research is cautioning us that the quality of public investment is determined by the overall quality of governance, transparency, contestability and openness of the allocation process. These attributes are essential to prevent the misuse of public funds as a means of redistributing political rents.[12] One expects the same to apply to the evaluation of the role of public funds in enhancing basic research. Further investigation of all these issues is needed in order to provide us with better policy guidelines.

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[12] See Tanzi and Davoodi (1997) and Everhart and Sumlinski (2001) and the reference therein. Everhart and Sumlinski (2001) concluded that "…corruption lowers the quality of public investment, and this poor quality public investment is associated with lower private investment."

Appendix A

The following model is used to identity possible variables applied in our empirical study. Awarding Nobel laureates and similar prizes is the outcome of a periodic contest among the stock of major recent contributions. The definition of "recent" is bounded by scholars' life expectancy. The intertemporal importance of major contributions is determined by the speed of diffusion of knowledge. Short of having a tractable way of comparing the relative importance of the major contributions, we adopt a simple threshold approach: all major scientific contributions vintage of the same year are treated as equal candidates for wining the prize contest. The arrival rate of major contributions in a country depends on the human capital in the country, potentially interacted with the 'global stock' of human capital in non linear ways due to scale and networking effects. Human capital evolves over time as the outcome of investment, adjusted for depreciation caused by aging, calamities [wars, etc…]. The investment in human capital depends positively on the scale of the economy that supports the research, like the real GDP, real GDP pre capita, etc.

Specifically, we sketch the following model for prizes:

Notation

$\phi_{i,t} =$ Number of major contributions occurring in country *i* during time *t* that may qualify for a prize in a given discipline, scaled by the importance of the contribution.

$\phi^{n}_{i,t-k}$ = contributions credited to country i dating to period t-k, net of the contributions that already won [i.e., $\phi^{n}_{i,t-k}$ is obtained by adjusting $\phi_{i,t-k}$ downward by the contributions that were already rewarded].

$\Phi_{i,t} = \sum_{k=0}^{T} \phi^{n}_{i,t-k} d_{t-k}$ = Stock of contributions credited to country i that may qualify for a prize at time t (net of contributions that were already awarded). The stock is obtained by applying the discount factor d_k to contributions going back T years ago, and T is the backward looking discounting horizon. In practice, T is bounded by scholars' life expectancy, and d_k is determined by the speed of diffusion of new contributions, apparently having an inverted *U* shape.

Assuming that the size of the prizes won relative to the pool of major new contributions is small, and that all contributions enter symmetrically, winning the prize is akin to sampling with replacement. Hence, the outcome of the Nobel contest may be approximated by generalized Bernoulli trials, with its convenient Gaussian properties.

Subject to all these assumptions, the probability wining a prize at time t by country i in a given discipline, $s_{i,t}$, is approximated by

$$\text{(A1)} \qquad s_{i,t} = \frac{\Phi_{i,t}}{\sum_{i=1}^{N} \Phi_{i,t}} \;;$$

where N is the number of countries engaging in active basic research.

We parameterize the flows of new contributions of country i as a proportion k_i of the human capital index, $\left[H_{i,t}\right]^{\beta}$;

$$\text{(A2)} \qquad \phi_{i,t} = k_i \left[H_{i,t}\right]^{\beta},$$

where $\beta > 0$ captures any scale effects. Complementarities between local and global knowledge may be captured by a CES aggregator:

$$\text{(A2')} \qquad \phi_{i,t} = k_i \left\{a_i \left[H_{i,t}\right]^{\gamma} + (1-a_i)\left[\overline{H}_t\right]^{\gamma}\right\}^{\frac{\beta}{\gamma}}$$

where $\overline{H}_t$ denotes the foreign human capital [i.e., the sum of the human capital of all other countries], and 1- a measures the externality associated with research attributed to foreign human capital. The human capital of country i follows a simple accumulation rule: a fraction $c_{i,t}$ the real GDP is invested into forming future human capital;[13] fraction $\delta_{i,t}$ depreciates, due to aging, wars, etc…

$$\text{(A3)} \qquad H_{i,t} = (1-\delta_{i,t})H_{i,t-1} + c_{i,t}Y_{i,t-1}.$$

To illustrate the model, we consider first the case where periods are set to cover a generation of scientists, say 25 years, such that $\delta_{i,t} = 1$, hence

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[13] If basic research is "luxury activity," $c_{i,t}$ would increase with the GDP per Capita. In these circumstances, our model predicts that the prize share of a country would depend positively on lagged GDP, and negatively on lagged population.

(A3') $H_{i,t} = c_{i,t} Y_{i,t-1}$

Suppose that we aggregate all the countries doing frontier research into 2 blocks, say the U.S. and all other countries (OAC) that are part of the research frontier. The OAC block is assumed to be composed of n symmetric countries. These assumptions allow us to solve the prize share of the U.S. as a function of the lagged real U.S. GDP relative to all other countries GDP, denoted by Γ (i.e., $\Gamma = Y_{US,-1}/Y_{AOC,-1}$). Assuming identical productivity structure across countries [i.e., both blocks have the same *k*, *c*, and *a*], we can infer that:

(A4) $$s_{US} = \frac{\left\{a\Gamma^{\gamma} + (1-a)\right\}^{\frac{\beta}{\gamma}}}{\left\{a\Gamma^{\gamma} + (1-a)\right\}^{\frac{\beta}{\gamma}} + n\left\{a(1/n)^{\gamma} + (1-a)(\Gamma + (n-1)/n)^{\gamma}\right\}^{\frac{\beta}{\gamma}}}.$$

A useful benchmark is the case where *a* = 1, corresponding to the absence of the global human capital externality:

(A4') $$s_{US} = \frac{\Gamma^{\beta}}{\Gamma^{\beta} + n^{1-\beta}}.$$

Figure 3a plots the U.S. share of the prizes predicted by our model as a function of the relative GDP share of the U.S./AOC. The bold curve corresponds to the benchmark case of two countries (n = 1), the absence of foreign human capital externality (*a* = 1), and significant scale effects ($\beta = 2$). The solid curve to the left of the bold one modifies the benchmark by considering the case where AOC are composed of two symmetric countries (n = 2; *a* =1). Note that more fractured composition of AOC reduces the research effectiveness there, increasing thereby U.S. share. The dotted curve modifies the benchmark by allowing modest human capital externality (n = 1, *a* = 0.95). Human capital externality increases the share of the smaller block, at the expense of the larger block. Figure 3b plots the same curves in the absence of returns to scale in research ($\beta = 1$). Removing scale effects considerably mitigates the prize share of the larger block (increasing thereby the share of the smaller block). It also implies simple additivity of the countries composting the block of AOC, and eliminates the inflection point.

The presence of scale effects implies that the association between the relative GDP shares and the prize share of the U.S. resembles a logistic curve. Specifically, (4') implies that for relatively small countries, the initial effect of higher GDP share on the prize share is nil: $ds_{US} / d\Gamma_{|\Gamma=0} = 0$ for $\beta > 1$. As the GDP share grows further, it increases the prize share at an accelerating rate, reflecting the growing impact of scale effects. This acceleration reaches its peak and the inflection point when the U.S. relative GDP equals $\tilde{\Gamma} = \left[n^{1-\beta} (\beta - 1)/(\beta + 1) \right]^{1/\beta}$. From then on, further increase of the GDP share increase the prize share at diminishing rates.[14] It also follows that greater scale effects implies higher threshold of relative GDP is needed in order to reach the "taking off" range associated with the accelerating increase in the prize share. Once this range has been reached, the takeoff is faster. This result is illustrated in Figure 4a, focusing on the case where the scale effect is magnified from 2 [the bold curve] to 4 [the dotted curve], drawn for the case where AOC is composed of a unique country. Figure 4b replicates this exercise for the case where the AOC is fractured into two symmetric countries. As one may expect, it implies that the U.S. takes off at a lower relative share.

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[14] These results follow from the observations that $ds_{US} / d\Gamma = \dfrac{\beta \Gamma^{\beta - 1} n^{1-\beta}}{[\Gamma^{\beta} + n^{1-\beta}]^2}$; and $sign\,[d^2 s_{US} / d\Gamma^2] = sign\,[(\beta - 1) n^{1-\beta} - (\beta + 1)\Gamma^{\beta}]$.

Appendix B – Data Sources and Descriptive Statistics

Table B1 – Data definitions and sources

	Data Definition	Source
Nobel	Nobel prize awards in Chemistry, Medicine and Physics, 1901-2005.	http://nobelprize.org/ http://www.almaz.com/nobel/
Wolf	Wolf Foundation prize awards in Agriculture, Chemistry, Mathematics, Medicine and Physics, 1978-2005.	http://www.wolffund.org.il/main.asp
Kyoto	Kyoto prize awards in Basic Science and Advanced Technology, 1985-2005.	http://www.kyotoprize.org/
Field	Fields medal in Mathematics, 1936-2002.	http://www.mathunion.org/medals/Fields/
GDP	Gross domestic product in million 1990 International dollars.	Maddison (2003)
POP	Population in thousands at mid-year	Maddison (2003)
WWI casualties	Total casualties in World War I	http://www.infoplease.com/ipa/A0004617.html
WWII casualties	Total casualties in World War II	http://www.secondworldwar.co.uk/casualty.html

Table B2 - Descriptive Statistics – Prizes – 5-years Dataset

	Number of prizes	Mean of observations	St. Dev. Of observations
Nobel	509	2.42	4.49
Wolf	199	0.95	3.40
Kyoto	46	0.22	1.05
Field	44	0.21	0.61

Table B3 - Prizes correlations – 5-years Dataset

	Kyoto	Field	Wolf
Nobel	0.63	0.57	0.67
Kyoto	1	0.41	0.64
Field	0.41	1	0.54

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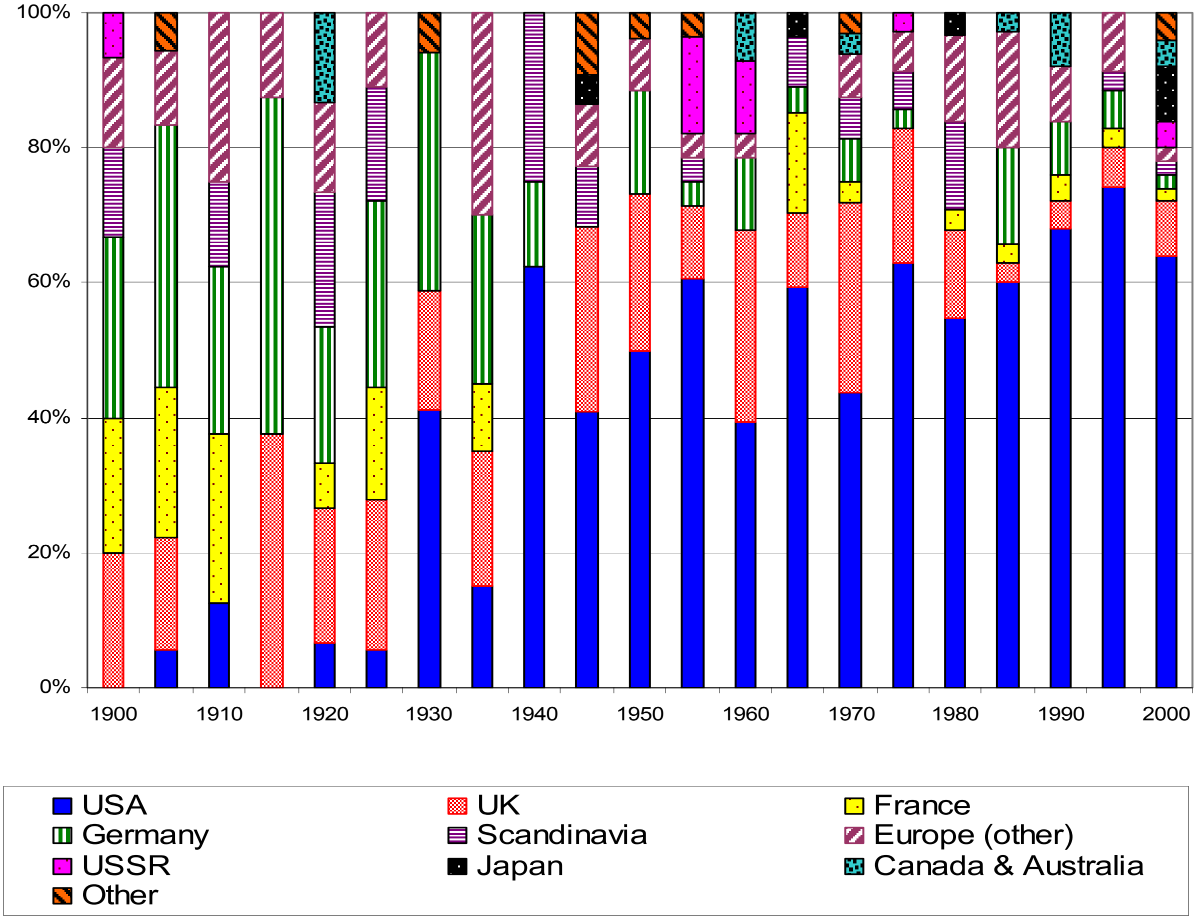

Figure 1A: Nobel Shares by Country

Nobel shares (out of total science Nobels awarded) 1900-2005

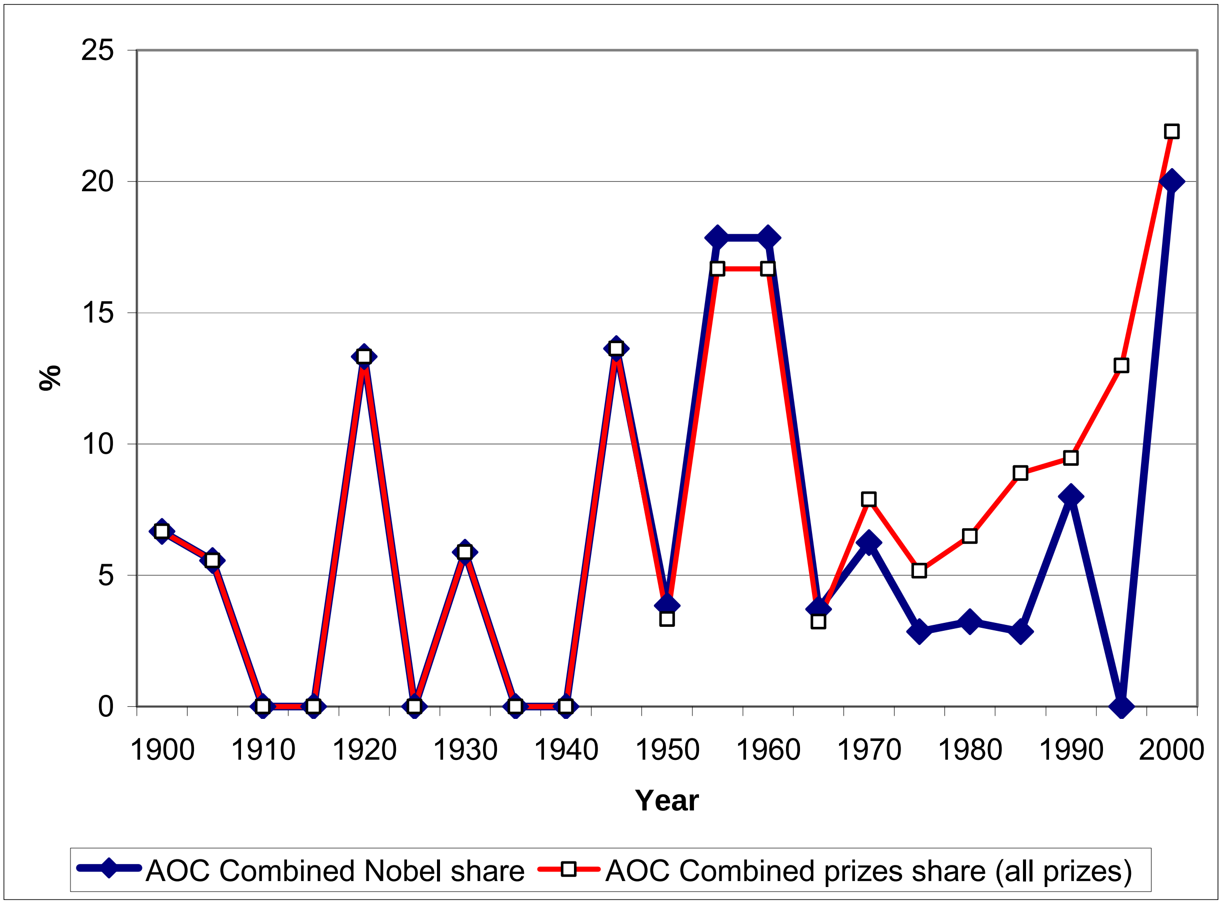

Figure 1B

Combined prize shares of AOC = All Countries - [Europe + U.S.]

The blue curve plots AOC share of Nobel prizes for basic science. The red curve plots AOC share of Nobel, Fields, Kyoto, and Wolf prizes for basic research.

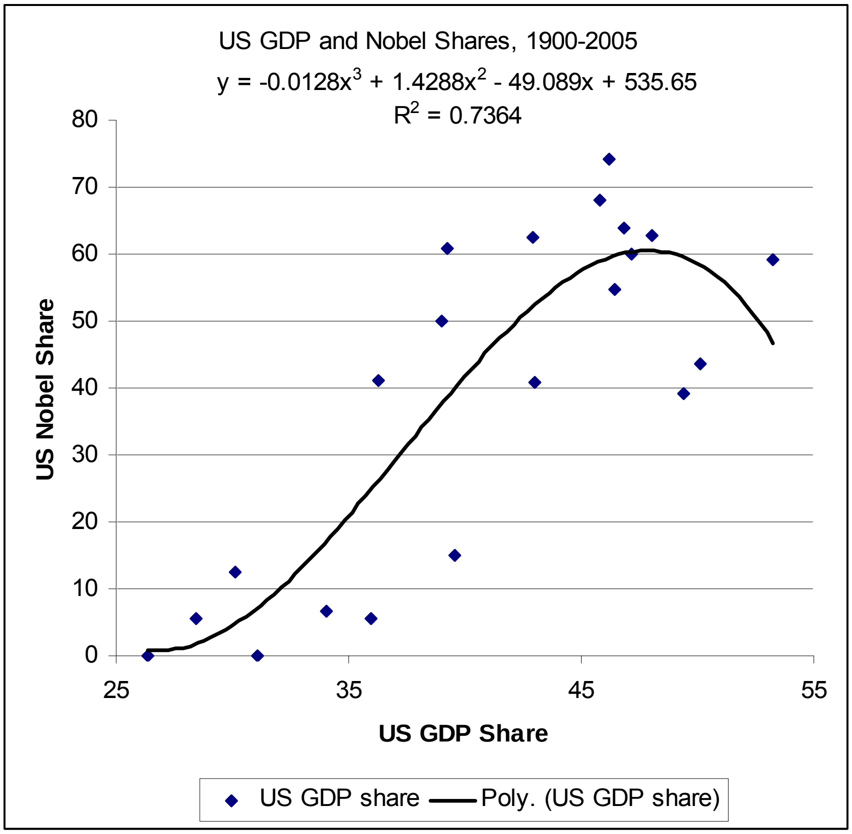

Figure 2: U.S. Nobel shares during the 20th century and lagged U.S. share of World GDP

The line corresponds to a third order polynomial trend line

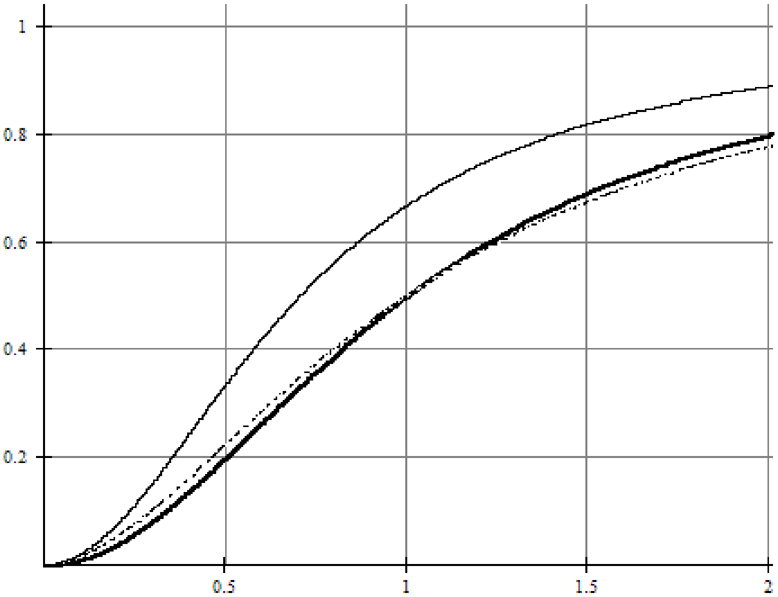

Figure 3A
U.S. prize share and the relative U.S./AOC GDP, with scale effects ($\beta = 2$).

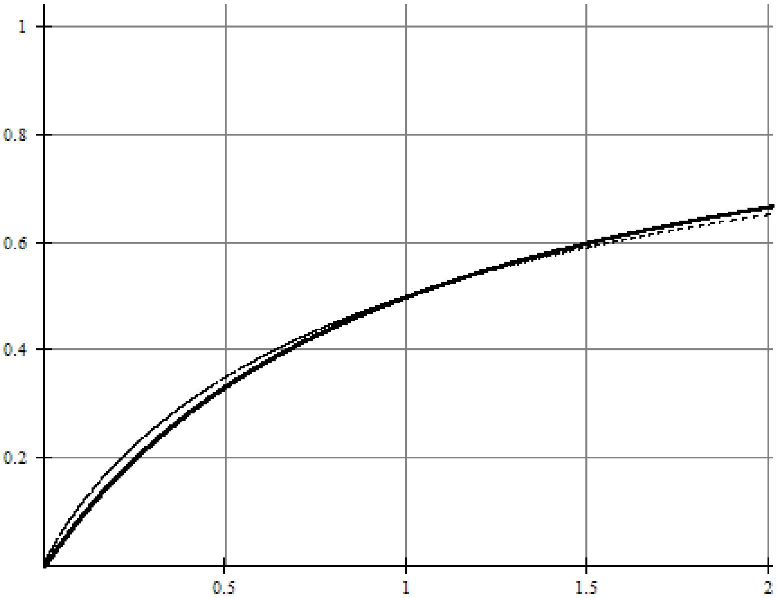

Figure 3B
U.S. prize share and the relative U.S./AOC GDP, no scale effects ($\beta = 1$).

The bold curve corresponds to the base case: the absence of externalities associated with foreign human capital, where the AOC block is composed of one country ($a = 1$; $n = 1$). The solid curve modifies the base case by assuming that the AOC block is composed of two symmetric countries ($a = 1$; $n = 2$). The dotted curve modifies the base case by assuming modest externality where foreign human capital increases the efficacy of domestic human capital ($a = 0.95$; $n = 1$).

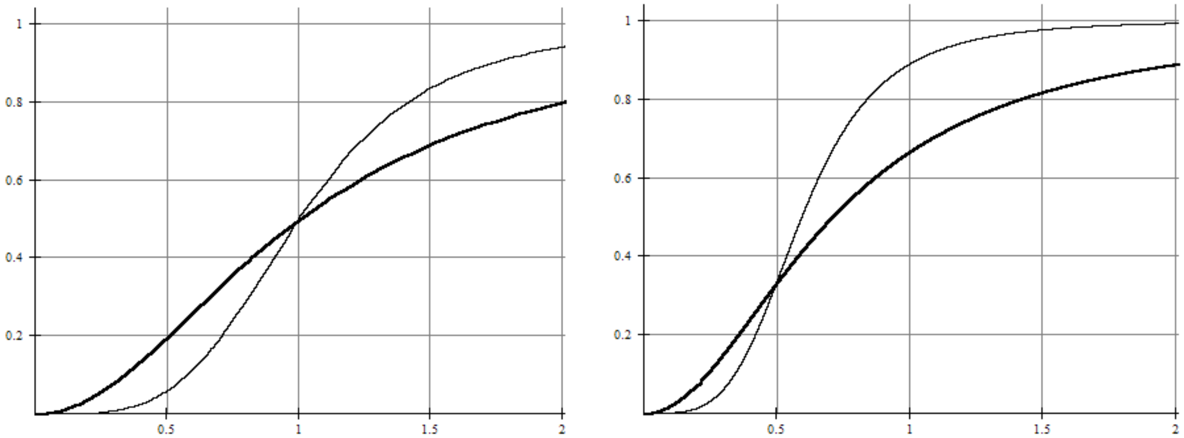

Figure 4A
AOC composed of one country

Figure 4B
AOC composed of two countries

U.S. prize share and the relative U.S./AOC GDP, varying scale effects

The bold curve corresponds to the base case of scale effect ($\beta = 2$), and no externality associated with foreign human capital ($a = 1$). The dotted curve corresponds to magnified scale effects, $\beta = 4$, $a = 1$. The top panel assumes symmetry, where the AOC is, like the U.S., composed on one country. The lower panel assumed fractured AOC, composed of two symmetric countries.

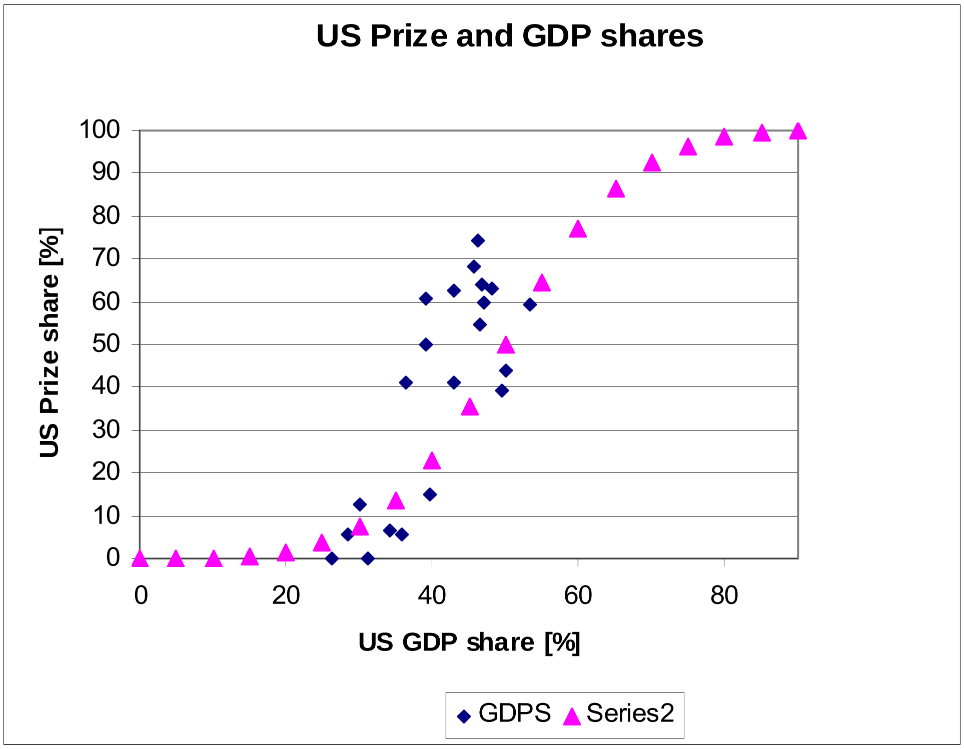

Figure 5
U.S. Nobel shares / lagged U.S. share of World GDP during the 20th centaury

Series 2 [triangles] correspond to the simulated model [plotting equation (4’), for $\beta = 3$, $n = 1$]

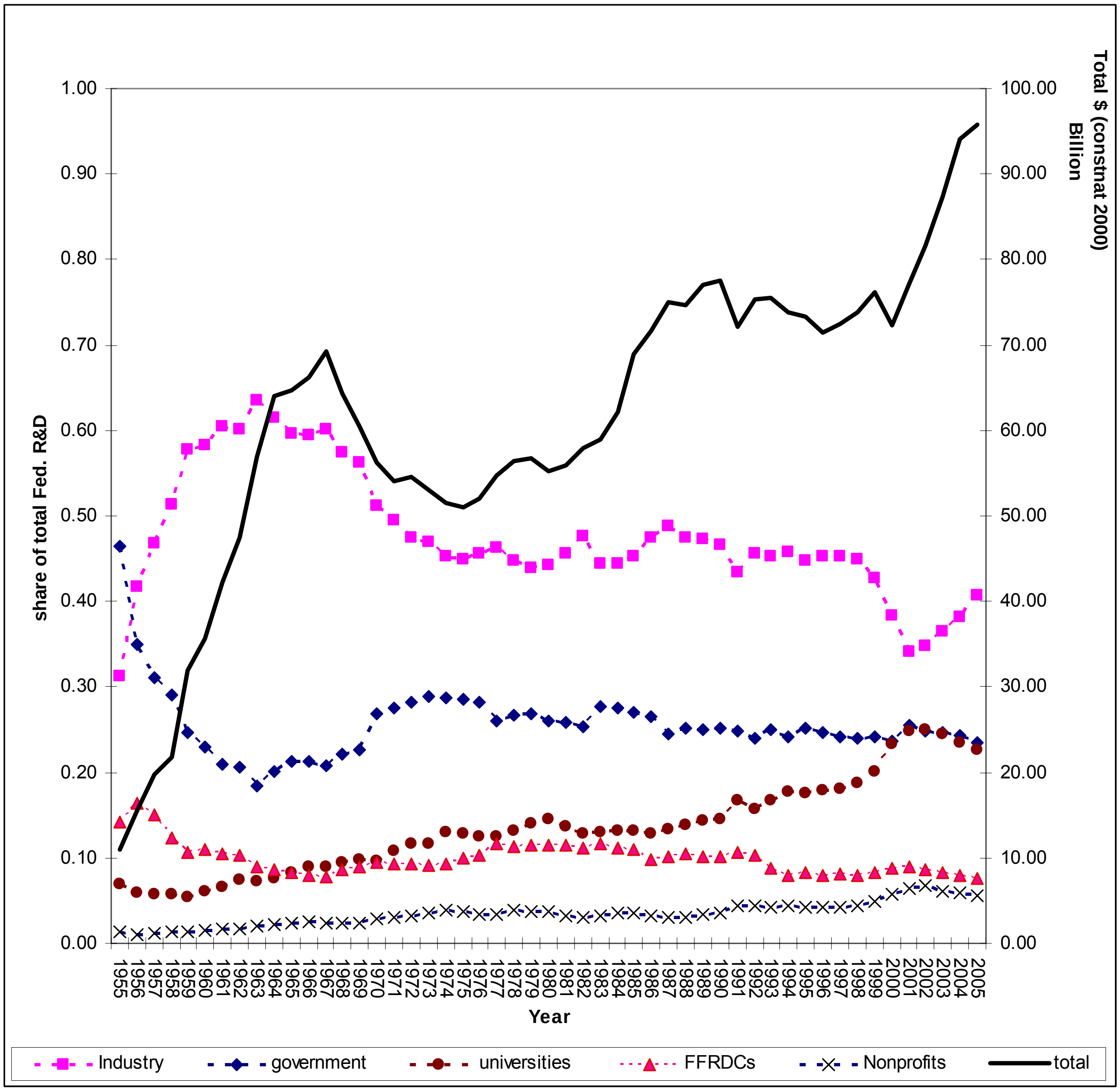

Figure 6

Federal supported R&D spending, 1955-2005 [total, and shares of R&D preformed by various sectors]

Right scale, the Solid curve: Total federal obligations for R&D, FY 1955–2005; Constant 2000 $ (billions)

Left scale: Share of federal total obligations for R&D supported by the government, by the performing sectors. The sectors, from top to bottom, are:
Industry, Government R&D, Universities, Federally Funded R&D centers (FFRDC), and Non-profits

Source: *Science and Engineering Indicators 2006* http://www.nsf.gov/statistics/seind06/c4/c4s2.htm

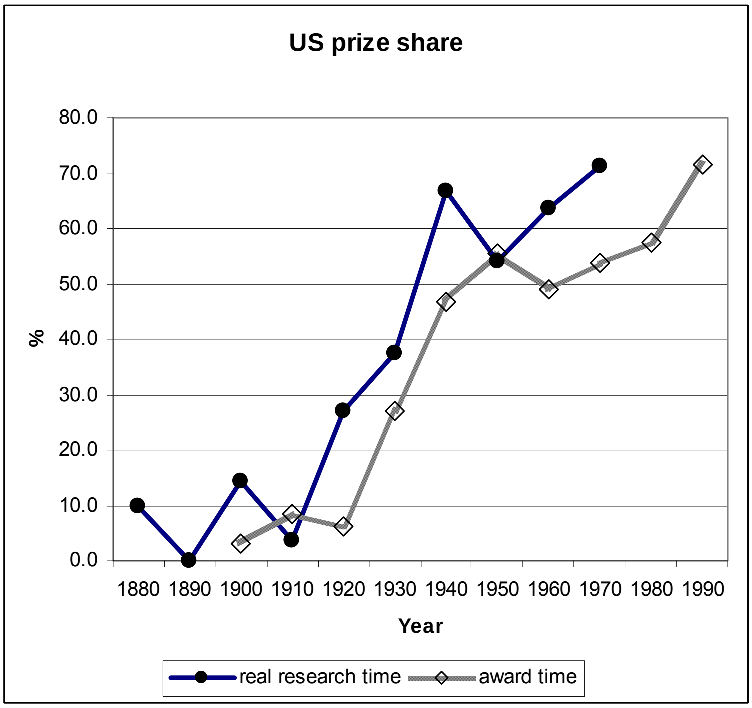

Figure 7a
US Nobel Prize share, real research time (1880s-1970s), award time (1900s-1990s)

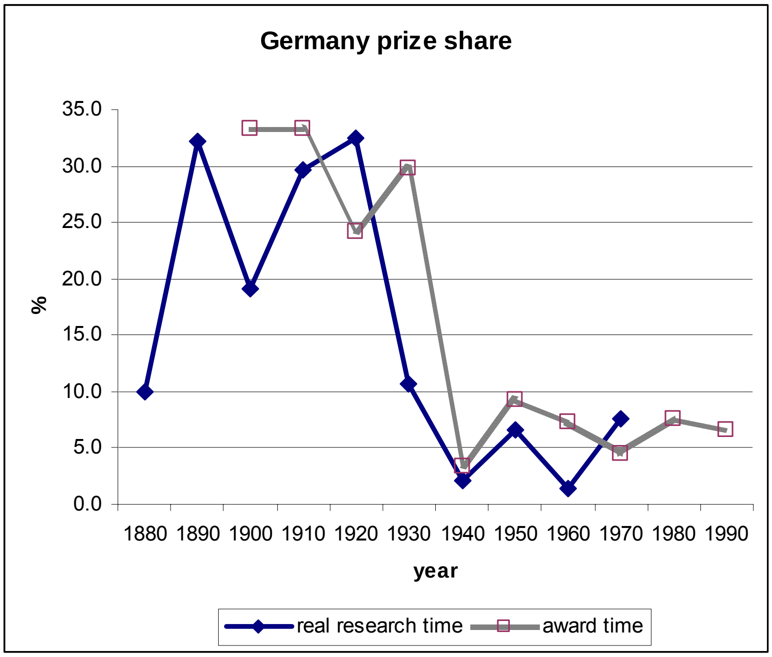

Figure 7b
Germany Prize share, real research time (1880s-1970s), award time (1900s-1990s)

Table 1A - Destinations for Immigrant Nobel Prize Winners (>5)

	1901-1935	1936-1970	1971-2005	Total
United States	3	29	44	76
United Kingdom	4	8	7	19
Switzerland	1	3	9	13
Germany	5	2	2	9
France	4	1	1	6

Number of prize-winners that immigrated to the destination countries listed in column 1.

Table 1B - Country of Origin for Immigrant Nobel Prize Winners (>5)

	1901-1935	1936-1970	1971-2005	Total
Germany	2	12	14	28
Austria	3	5	3	11
United Kingdom	1	1	6	8
Canada	0	2	5	7
Hungary	1	3	3	7
Poland	2	2	3	7
Russia	1	2	2	5
Italy	1	2	3	6
Netherlands	1	1	3	5
France	2	2	1	5
China	0	3	2	5

Number of prize-winners that emigrated from the countries-of-origin listed in column 1.

Table 2A – Benchmark Regression – 10-years Data

LHS:	Nobel			All Prizes		
	(1)	(2)	(3)	(4)	(5)	(6)
GDP/W	1.021*** (8.169)		1.622*** (13.162)	1.070*** (10.515)		1.536*** (14.910)
POP/W		-0.057 (0.453)	-0.619*** (6.786)		0.110 (1.119)	-0.456*** (6.958)
σ	15.582*** (11.549)	22.562*** (11.942)	12.053*** (11.712)	12.905*** (12.612)	19.808*** (12.834)	10.214*** (12.632)
Observations	100	100	100	100	100	100
Decomposition fit measure	0.23	0.16	0.47	0.29	0.11	0.52

Note: Dependent variable is the prize share (in %) per country-decade observation. The model is estimated with a Tobit methodology. T-statistics in parentheses; significance levels are 10% *, 5% ** and 1%***. σ is the estimated standard deviation of the error term. The decomposition fit measure is a goodness-of-fit measure for non-linear models (for details see Greene, 2002).

Table 2B – Benchmark Regression – 5-years Data

LHS:	Nobel			All Prizes		
	(1)	(2)	(3)	(4)	(5)	(6)
GDP/W (t-4)	0.610*** (8.032)		1.062*** (13.526)	0.673*** (10.742)		1.034*** (15.773)
POP/W (t-4)		-0.031 (1.029)	-0.176*** (7.107)		0.012 (0.523)	-0.131*** (7.407)
σ	18.240*** (14.549)	24.438*** (14.117)	14.814*** (14.662)	15.398*** (15.977)	21.700*** (16.583)	12.659*** (16.002)
Observations	205	201	201	201	201	201
Decomposition fit measure	0.18	0.21	0.34	0.20	0.15	0.38

Note: Dependent variable is the prize share (in %) per country-5-years observation. The model is estimated with a Tobit methodology. T-statistics in parentheses; significance levels are 10% *, 5% ** and 1%***. σ is the estimated standard deviation of the error term. The decomposition fit measure is a goodness-of-fit measure for non-linear models (for details see Greene, 2002).

Table 3A – Scale Regressions – 10-years Data

LHS:	Nobels			All Prizes		
	(1)	(2)	(3)	(4)	(5)	(6)
GDP/W	0.674**	0.849***	1.079***	0.782***	0.873***	1.120***
	(2.533)	(7.095)	(4.901)	(3.489)	(8.439)	(5.913)
POP/W	-0.529***	-0.318***	-0.354***	-0.395***	-0.236***	-0.263***
	(6.154)	(4.792)	(4.908)	(6.214)	(4.597)	(4.718)
Pre-1930 Germany		15.984***			15.000***	
		(3.794)			(4.062)	
Post-1930 U.S.		41.962***	42.189***		36.366***	37.469***
		(8.830)	(6.064)		(8.772)	(6.185)
Scandinavia		2.174			1.943	
		(0.800)			(0.817)	
$(GDP/W)^2$	0.039***		-0.007	0.031***		-0.009
	(3.957)		(0.681)	(3.743)		(0.958)
σ	11.166***	8.182***	8.934***	9.570***	7.176***	7.826***
	(11.803)	(11.682)	(11.647)	(12.698)	(12.605)	(12.599)
Observations	100	100	100	100	100	100
Decomposition fit measure	0.60	0.79	0.75	0.64	0.81	0.77

Note: Dependent variable is the prize share (in %) per country-decade observation. The model is estimated with a Tobit methodology. T-statistics in parentheses; significance levels are 10% *, 5% ** and 1%***. σ is the estimated standard deviation of the error term. The decomposition fit measure is a goodness-of-fit measure for non-linear models (for details see Greene, 2002).

Table 3B – Scale Regressions – 5-years Data

LHS:	Nobels			All Prizes		
	(1)	(2)	(3)	(4)	(5)	(6)
GDP/W (t-4)	0.362**	0.582***	0.593***	0.502***	0.618***	0.716***
	(2.080)	(6.618)	(3.452)	(3.465)	(8.457)	(4.987)
POP/W (t-4)	-0.156***	-0.103***	-0.123***	-0.117***	-0.076***	-0.091***
	(6.465)	(5.005)	(5.223)	(6.702)	(5.022)	(5.220)
Pre-1930 Germany		24.069***			22.823***	
		(7.577)			(6.196)	
Post-1930 U.S.		35.104***	27.354***		30.521***	26.290***
		(7.368)	(3.593)		(7.575)	(4.051)
Scandinavia		1.970			3.011	
		(0.715)			(1.318)	
$(GDP/W)^2$ (t-4)	0.022***		0.004	0.017***		0.000
	(4.529)		(0.684)	(4.117)		(0.054)
σ	14.281***	11.783***	13.339***	12.256***	10.072***	11.461***
	(14.762)	(14.672)	(14.587)	(16.089)	(16.020)	(15.971)
Observations	201	201	201	201	201	201
Decomposition fit measure	0.46	0.60	0.52	0.49	0.65	0.56

Note: Dependent variable is the prize share (in %) per country-5-years observation. The model is estimated with a Tobit methodology. T-statistics in parentheses; significance levels are 10% *, 5% ** and 1%***. σ is the estimated standard deviation of the error term. The decomposition fit measure is a goodness-of-fit measure for non-linear models (for details see Greene, 2002).

Table 4 –Regressions – WW Casualties – 10-years data

LHS:	Nobels (1)	 (2)	 (3)	 (4)	 (5)
GDP/W	1.627***	1.687***	1.705***	0.594	1.056***
	(13.021)	(13.433)	(13.631)	(1.839)	(4.031)
POP/W	-0.619***	-0.624***	-0.625***	-0.520	-0.349***
	(6.792)	(7.069)	(7.161)	(6.005)	(4.887)
WW Casualties (t)	-9.439	12.680	11.601	52.450	46.318
	(0.210)	(0.278)	(0.257)	(1.183)	(1.321)
WW Casualties (t-1)		-13.320	4.107	38.118	29.432
		(0.307)	(0.091)	(0.881)	(0.860)
WW Casualties (t-2)		-56.671	-58.113	-4.451	-13.155
		(1.310)	(1.357)	(0.103)	(0.385)
WW Casualties (t-3)		-84.323*	-85.153*	-46.995	-51.798
		(1.785)	(1.821)	(1.029)	(1.432)
WW Casualties (t-4)			-60.345		
			(1.298)		
$(GDP/W)^2$				0.041***	-0.007
				(3.646)	(0.578)
Post-1930 U.S.					42.263***
					(6.233)
σ	12.051***	11.669***	11.553***	10.989	8.701***
	(11.712)	(11.709)	(11.714)	(11.799)	(11.632)
Observations	100	100	100	100	100
Decomposition fit measure	0.47	0.51	0.52	0.61	0.76

Note: Dependent variable is the prize share (in %) per country-decade observation. The model is estimated with a Tobit methodology. T-statistics in parentheses; significance levels are 10% *, 5% ** and 1%***. σ is the estimated standard deviation of the error term. The decomposition fit measure is a goodness-of-fit measure for non-linear models (for details see Greene, 2002).

Table 5 –Regressions 1975-2004 – 5-years Data

LHS:	(1) 1975-2004	(2) 1900-2004 No U.S.
GDP/W (t-4)	0.192*	0.685***
	(1.714)	(4.238)
POP/W (t-4)	-0.084***	-0.114***
	(7.923)	(4.879)
	0.031***	0.009
(GDP/W)^2 (t-4)	(10.213)	(0.948)
σ	5.095***	10.699***
	(10.324)	(14.728)
Observations	60	180
Decomposition fit measure	0.93	0.13

Note: Dependent variable is the prize share (in %) per country-5-years observation. The model is estimated with a Tobit methodology. T-statistics in parentheses; significance levels are 10% *, 5% ** and 1%***. σ is the estimated standard deviation of the error term. The decomposition fit measure is a goodness-of-fit measure for non-linear models (for details see Greene, 2002).