The Contribution of International Graduate Students to US Innovation

Gnanaraj Chellaraj, Keith E. Maskus, and Aaditya Mattoo*

Abstract

The impact of international students in the United States on innovative activity is estimated using a model of idea generation. Results indicate that the presence of foreign graduate students has a significant and positive impact on both future patent applications and future patents awarded to university and non-university institutions. Our central estimates suggest that a 10% increase in the number of foreign graduate students would raise patent applications by 4.5%, university patent grants by 6.8% and non-university patent grants by 5.0%. Thus, reductions in foreign graduate students from visa restrictions could significantly reduce US innovative activity. Increases in skilled immigration also have a positive, but smaller, impact on patenting.

1. Introduction

In this paper, we explore the statistical roles that foreign graduate students play in expanding US innovation, as measured through patent applications and grants. It is often remarked that the ability of American universities to undertake scientific research which results in innovative technologies and products, has become increasingly dependent on the presence of technically trained international graduate students. Surprisingly, however, this basic proposition has not been systematically examined in an empirical context.

This issue has taken on considerable importance in recent years. Since the advent of far tighter restrictions on the issuance of US education visas after September 11, 2001, immigration policy for foreign graduate students has become the subject of intense debate. Many argue that the policy shift will harm the nation’s innovation capacity. For example, US university officials are concerned that these restrictions could cause “. . . a crisis in research and scholarship . . .”1 The same point finds its way into editorials.2 Lawrence Summers, the former president of Harvard, warned the US State Department that the decline in foreign students threatens the quality of research coming from US universities.3

If limits and delays in the number of foreign graduate students in science and engineering (S&E) and, more generally, of foreign skilled workers has the long-term impact of limiting innovation, productivity would suffer. Recent evidence indicates that productivity growth in the United States has been generated largely by advances in

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technology (Basu et al., 2003; Gordon, 2004). Technological improvements largely have been driven by the rate of innovation, which has been increasing in recent years as measured by the rapidly growing number of patents awarded to US industries and universities (Kortum, 1997; Hall, 2004).

The United States remains at the cutting edge of technology, despite frequent complaints about quality deficiencies in its secondary education system. Indeed, among the major developed countries and the newly industrialized countries, the United States ranks near the bottom in mathematics and science achievement among eighth graders. What may reconcile these factors is that the United States attracts large numbers of graduate students and skilled immigrants who enter such technical fields as medicine, engineering, and software design. Indeed, the United States sustains a significant net-export position in the graduate training of scientists, engineers, and other technical personnel.

It is likely that international graduate students are important inputs into the US innovation capacity. In this paper, we estimate an innovation production function in which graduate students are an input into the development of new ideas, both at universities and in the private sector. We also consider the contribution of skilled immigrants, defined as those arriving under employment-based visas. Results of the econometric analysis indicate that, holding constant the presence of total graduate students and the cumulative number of doctorates in science and engineering, increases in the presence of foreign graduate students have a positive and significant impact on future US patent applications and grants awarded to both firms and universities. This finding extends weakly to the relative presence of skilled immigrants in the labor force. The results are robust to treatment for serial correlation through estimation of cointegrating relationships. Put simply, we find that enrollments of foreign graduate students have a strong and positive impact on the development of ideas in the United States.

The paper proceeds as follows. In the next section we review literature that motivates this study. In section 3 we develop a simple model and set out the econometric specification. In section 4 we provide results and discuss their economic and policy significance. In section 5 we conclude.

2. Background and Literature Review

The question of whether skilled immigration bring net benefits or costs, is much discussed in media and policy circles (Borjas, 2005a, b; 2006). It is evident that a major component of any gains must be the contribution of skilled immigrants, and graduate and post-doctoral students, to an economy’s capacity to innovate and raise productivity. As noted earlier, the question has not been the subject of systematic empirical analysis. However, there are related strands of literature that help motivate our analysis.

Basic Economic Models

Labor economists have focused on the static implications of immigration into the United States for domestic wage inequality and prices (Briggs, 1996). It is evident that inflows of unskilled workers, which have been a rising share of US immigrants in recent decades, could reduce the wages of domestic unskilled labor and contribute to rising wage inequality (Borjas et al., 1997). However, this view has been disputed in recent studies (Ottaviano and Peri, 2005; Card, 2005; Chiquiar and Hanson, 2005).

Davis and Weinstein (2002) argued that a single-factor Ricardian model could be used to analyze the implications of factor inflows into the United States. Aggregating
labor and capital into a single factor, they calculated simply that such inflows implied a loss of some $72 billion per year for US natives relative to a free-trade baseline without immigration. The reason is that the incoming factors contribute to production capacities without expanding per-worker productivity, leading to significant losses on the terms of trade and lower real wages.

In our view, both forms of analysis are misleading because they fail to account for at least two important issues. First, in a broader static model, immigrants can raise the productivity and real wages of native skilled workers. Second, and more relevant for our analysis, is the possibility that skilled migrants may increase innovation, thereby contributing to future productivity gains (and real wages) of native workers. For example, Levin and Stephan (1999) argued that foreign-born scientists play a disproportionate role in generating knowledge in the United States. Thus, the presence of international graduate students could support rising aggregate real incomes in the long run. Ultimately, the impacts of immigration and education on real incomes through innovation are an empirical issue.

Indeed, pessimistic claims about the impacts of foreign workers seem inconsistent with continued political support, arising from the high-technology sectors in the United States, for sustaining immigration of skilled workers and S&E students. Thus, an essential motivation for our paper is to investigate whether this support is rooted in the dynamic innovation impacts of such foreign students training in the United States.

Foreign Graduate Students and Skilled Immigration

To provide context, note that annual flows of skilled immigrants into the United States rose by a factor of more than 30 in the period 1960–2000, while those of international students rose by a factor of 8.2. An important impetus was the Hart–Cellar Immigration Act of 1965, which removed the prevailing National Origins quotas and resulted in greater flows of skilled immigration and foreign students. These trends were accelerated after passage of the Kennedy–Rodino Immigration Act of 1990. Studies by Cobb-Clark (1998) and Antecol et al. (2003) indicate that legislative reforms resulted in a sharp increase in the flow of talented international workers into the United States. Further, there is an important positive relationship between human capital investment and the likelihood of immigration (Duleep and Regets, 1999).

Data demonstrate further that the number of skilled immigrants, as a proportion of the US labor force, increased sharply after 1965, and especially after 1990, while foreign graduate students, as a percentage of total graduate students, went up rapidly after 1975. It is worth noting that foreign graduate students have a high propensity to remain within the United States, at least for the early proportion of their careers (Bratsberg and Ragan, 2002). Aslanbeigui and Montecinos (1998) found that 45% of international students from developing countries planned to enter the US labor market for a time, and 15% planned to stay permanently.

Current US policy is marked by schizophrenia. Despite legislative attempts since the early 1980s to restrict university enrollments and post-graduate employment of international students, the United States still allows a significant proportion to stay and work after graduation and, in a majority of cases, grants them permanent residence (Diaz-Briquets and Cheney, 2003). Indeed, a recent taskforce on innovation recommended that the United States make it easier for foreign students in S&E fields to remain in the United States after graduation.

On a negative note, Borjas (2002) speculates that foreign students in the United States benefit the economy by spending some $1 billion a year, but this gain is more
than offset by the costs of taxpayer-financed grants and subsidies at public universities. In another paper, Borjas (2005a) found a strong negative correlation between the enrollment of native men in US graduate programs and the enrollment of foreign students. Institutions experiencing the largest increase in foreign enrollment also experienced the steepest fall in the enrollment of native males.

This result suggests that domestic and foreign graduate students are highly substitutable, but other information indicates that this assertion is questionable. Although data on the quality of domestic graduate student applicants, compared to their international counterparts, are not readily available, results from TIMSS and other international tests indicate that the native US student pool for S&E programs is limited due to lower math and science achievement. This suggests that student populations are not readily substitutable, and that university technical training programs may have increased their demand for foreign students.

Thus, it is not surprising that a recent study demonstrated a sharp drop in the proportion of PhDs in science and engineering awarded to US-born males between the early 1970s and 2000 (Freeman, 2005). In 1966, US-born males accounted for 71% of science and engineering PhD graduates, while 6% were awarded to US-born females, and only 23% of doctoral recipients were foreign-born. The situation was reversed by 2000, when only 36% of doctoral recipients were US-born males, 25% were US-born females, and 39% were foreign-born. Contradicting Borjas (2005a), Freeman found that foreign students were not substituted for domestic students. The number of PhDs granted to undergraduates from US institutions, most of whom were US citizens, did not change much during this period, while there was substantial growth in the number of foreign bachelor’s graduates obtaining US doctorates. Thus, the change in proportion was mostly due to the expansion of PhD programs, with a majority of the new slots taken by foreign students rather than through substitution.

These same trends explain the fact that the proportion of foreign-born faculty with US doctoral degrees at US universities has gone up sharply during the past three decades, from 11.7% in 1973 to 20.4% in 1999. For engineering, it rose from 18.6% to 34.7% in the same period.

In the last few years, however, there has been a steep decline in foreign student applications for admission into US universities, and a corresponding increase in applicants to universities in other countries. Foreign student enrollment declined by 4.3% in the United States between 2001 and 2004, while it increased by 7.7% in the United Kingdom, 25% in Canada, 94% in Australia, 99% in New Zealand, and 57% in Singapore. These shifts are due both to difficulties in obtaining US visas since September 2001, and to the fact that some countries are catching up to the United States with regard to attracting foreign students and skilled labor from abroad (Hira, 2003).

**University Research and Patenting**

In the United States, patenting of new inventions by universities began to accelerate during the 1960s (Henderson et al., 1998; Foray, 2004). University innovation and patenting were boosted by the Bayh–Dole Act of 1980, which allowed US universities to commercialize research results (Mowery et al., 2001; Sampat et al., 2003). Currently, the determinants of university patenting in the United States and its implications for the economy are a central subject for inquiry (Thursby and Thursby, 2002; Thursby and Kemp, 2002; Jensen and Thursby, 2001; Kim et al., 2007; Jaffe and Trajtenberg, 2005). Both national governments and private industries play a significant role in financing
research that supports patenting (Scotchmer, 2005; Link and Scott, 2003; 2005; Branstetter and Ogura, 2005).

With one exception, prior studies of university patenting have not analyzed the role of foreign graduate students, as inputs into the innovation production function. That exception is Stephan et al. (2005), which related patenting by US universities to the number of foreign-born doctorates and post-doctoral graduate students. They found that the relationship between patent counts and international PhDs who are permanent residents is positive and significant, while it is negative for those on temporary visas. Patents also depend positively on the presence of international post-doctoral students. Thus, their findings provide partial support for the hypothesis advanced here, though it leaves open a number of questions for further study of the role played by the foreign-born in American innovation.

That role could be important, as most countries in the world are not in a position to produce domestically all the skilled labor necessary for rapid technological development and innovation. It seems plausible that a relatively open skilled immigration policy could play an important role in innovation and follow-on growth.

3. Modeling Framework and Data

To estimate the contribution of skilled immigrants and foreign graduate students to US innovation, we modify the “national ideas production function” that is widely used in innovation studies (Porter and Stern, 2000; Stern et al., 2002). This may be written in general form as

\[ \dot{A}_t = \delta H_{A,t} A^\phi. \]  

Thus, the rate of new ideas produced depends on both the allocation of resources to the R&D sector \( (H_{A,t}) \), the productivity of those resources \( (\lambda) \), the stock of ideas already in existence \( (A_t) \), and the ability of that stock to support new invention \( (\phi) \). Note that if \( \phi > 0 \), prior research increases current R&D productivity (the “standing on shoulders” effect), but if \( \phi < 0 \), prior research has discovered the easier ideas and new invention becomes more difficult.

Our measures of new ideas production are total patent applications, total patents awarded, and patents granted to US-based universities and other institutions and firms. All of these data refer to activities within the United States. Patents are not an ideal measurement of innovative output, primarily because patents vary widely in their economic and technical significance (Griliches, 1990). However, patenting activity is the most commonly used proxy in innovation studies, and does capture three important aspects of innovation (Kortum, 1997; Stern et al., 2002). First, patents reflect an important part of innovative output, and are likely correlated with others, such as trade secrets and copyrights. Second, to be awarded a patent, inventions must be novel and non-obvious, suggesting that patent grants capture something new. Third, it is costly to apply for a patent, so the patenting entity believes there is something economically valuable about its technological innovation.

The primary novelty of our approach is in the definition of \( H_{A,t} \). In prior studies, these resources have been measured by R&D expenditures (perhaps broken into university and non-university sources), and scientists and engineers. We retain the use of these basic variables, but incorporate international students and skilled immigrants as components of the inputs into idea generation. We permit the productivity of each resource to differ, as follows.
Here, $H_F$ is the flow (enrollments) of international graduate students, $H_G$ is the flow (enrollments) of total graduate students, $H_I$ is the number of skilled immigrants in the country, $H_S$ is the number of total PhD engineers and scientists, and $H_R$ is expenditure on R&D. Note that there is some overlap between skilled immigrants and engineers and scientists, but it is not possible with available data to distinguish sharply between these factors.

To capture the stock of existing knowledge ($A_t$), we employ the accumulated number of patents awarded. This variable captures the technical ability of the economy at any time, to translate its knowledge stock into a stream of new inventions. Finally, the parameter $\delta$ in equation (1) captures the aggregate ability of the economy (or the university sector), to convert inputs and knowledge stock into new ideas. For this purpose, we take $\delta$ to be a function of time (capturing changes in US ideas of productivity) and a key policy change, the passage of the Bayh–Dole Act in 1980, which should have changed the ability of universities (and perhaps enterprises) to convert technical inputs into new ideas.

To implement this structure econometrically, we must account for two factors. First, there is a lag between the time research inputs are utilized and the granting of a patent. It takes around five years, on average, to conduct research in an area and apply for patents, and another two years for patents to be awarded (Popp et al., 2004). The exact times for applications and awards vary by field of invention. For pharmaceuticals, it could take as long as 15 years for patent applications and a further two years for the patent award (DiMasi et al., 2003). In contrast, in some areas of engineering it could take as little as three years for patent application and one year for patent awards. Because we use aggregate data, we must employ a compromise. Thus, in the primary specification we entertain a five-year lag for patent application and a seven-year lag for patents awarded. We also test for the robustness of this assumption by using other lags.

Second, because we undertake time-series estimation, there may be problems with stationarity in the levels of patents, immigrants, and graduate students. Over the estimation period, the absolute numbers of foreign students and patent applications have increased steadily. Thus, we scale relevant variables so they are measured in proportion to the aggregate labor force, except that the number of foreign students is measured in proportion to total graduate students in the country. We also incorporate a time trend into all specifications. These procedures offer some protection from a finding of spurious correlations in integrated data, but cannot eliminate that possibility. Thus, we also estimate relevant cointegrating relationships to verify the robustness of our results.

Putting these ideas together yields two specifications. Our basic econometric specification, estimated in logs, is as follows.

\[
IPA_{t+5} = \alpha_1 + \lambda_{F1}FORTGR_t + \lambda_{I1}IMCUM_t + \lambda_{S1}SK_t + \lambda_{R1}RD_t + \phi_{11}TOTPATSTOCK_t + \delta_{B1}BD_t + \theta_{11}TIME_t + \eta_{1t}
\]

\[
IPG_{t+7} = \alpha_2 + \lambda_{F2}FORTGR_t + \lambda_{I2}IMCUM_t + \lambda_{S2}SK_t + \lambda_{R2}RD_t + \phi_{22}TOTPATSTOCK_t + \delta_{B2}BD_t + \theta_{22}TIME_t + \eta_{2t}.
\]

In the first equation, the dependent variable is total patent applications as a percentage of the US labor force, five years after inputs are employed. These inputs include foreign graduate students as a percentage of total graduate students (FORTGR), skilled immigrants as a proportion of labor force (IMCUM), PhDs employed in S&E as

\[H^2_{A3} = H^2_{F3}H^2_{G3}H^2_{I3}H^2_{S3}H^2_{R3}\]
a percentage of labor force (SK), and the ratio of real research and development expenditures to the labor force (RD). We employ FORTGR to permit identification of the impact of foreign graduate students, holding constant the total presence of graduate students in US universities.

Regarding skilled immigrants, we wish to have a measure that is comparable to such other variables as graduate students and engineers and scientists, which are defined as the total amount in activity (e.g., added over all enrollments for students rather than new enrollments). Therefore, we define the variable IMCUM, which is the number of skilled immigrants cumulated over the preceding six-year period, divided by the labor force.

The estimation also includes the knowledge stock, as proxied by cumulative total patent stock over the past five years (TOTPATSTOCK), again divided by the labor force. Finally, there is a dummy variable capturing the Bayh–Dole Act, which takes on the value zero before 1980 and unity from 1980 onwards. The second equation is for patent grants and has the same structure, except that the independent variables enter with a seven-year lag.

This first specification does not distinguish between university and non-university patenting activity, because data from the US Patent and Trademark Office did not make this distinction for patent applications in early years of the sample. However, patent grants are broken out in this way. Thus, a second series of equations distinguishes between patents awarded to universities and patents awarded to other organizations:

\[
\text{IPA}_{t+5} = \alpha_1 + \lambda_{F1}\text{FORTGR}_t + \lambda_{I1}\text{IMCUM}_t + \lambda_{S1}\text{SK}_t + \lambda_{R1}\text{RD}_t + \phi_1\text{TOTPATSTOCK}_t + \delta_{B1}\text{BD}_t + \theta_1\text{TIME}_t + \eta_1t
\]

\[
\text{UIPG}_{t+7} = \alpha_2 + \lambda_{F2}\text{FORTGR}_t + \lambda_{I2}\text{IMCUM}_t + \lambda_{S2}\text{SK}_t + \lambda_{R2}\text{URD}_t + \phi_2\text{UPATSTOCK}_t + \delta_{B2}\text{BD}_t + \theta_2\text{TIME}_t + \eta_2t
\]

\[
\text{OIPG}_{t+7} = \alpha_3 + \lambda_{F3}\text{FORTGR}_t + \lambda_{I3}\text{IMCUM}_t + \lambda_{S3}\text{SK}_t + \lambda_{R3}\text{ORD}_t + \phi_3\text{OPATSTOCK}_t + \delta_{B3}\text{BD}_t + \theta_3\text{TIME}_t + \eta_3t
\]

The first equation is the same as the initial equation in the pair listed above. The second equation captures patents granted to universities (UIPG) after a seven-year lag. It employs the same variables, except it incorporates university real R&D expenditures divided by the labor force (URD) and the cumulated university patent stock divided by labor force (UPATSTOCK). The third equation captures non-university patents awarded (OIPG) after a seven-year lag, and incorporates scaled non-university real R&D expenditures (ORD) and scaled other patent stock (OPATSTOCK). All three equations contain the Bayh–Dole dummy and a time trend.

The independent variables in the second set of equations are expected to be positively related to the dependent variables. Patent applications and awards should increase with the stock of cumulated knowledge. Increases in technical inputs, including R&D expenditures, the proportion of international graduate students, and the proportion of skilled immigrants should expand patenting activity after a lag. University (and possibly non-university) patents awarded as a proportion of labor force, should be positively affected by the Bayh–Dole Act of 1980.

A final observation is that graduate enrollments, and the split of graduate students between domestic and foreign students, may be sensitive to the state of the business cycle (Sakellaris and Spilimbergo, 2000). Failure to control for this possibility could risk finding spurious results and, accordingly, we incorporate into all equations the US unemployment rate lagged in the same way as other independent variables.
These econometric models are implemented with annual data over the period 1963 to 2001 for patent applications, and from 1965 to 2001 for patent grants. The data were collected from a variety of sources. Figures on US graduate students were gathered from the US Department of Education, Statistics Quarterly. No separate data were available on the number of US graduate student enrollment in S&E for the entire period of analysis. Data on international graduate students were gathered from Open Doors, the publication of Institute for International Education. No data were available on international graduate students in S&E for the period prior to 1983 and, hence, total international graduate students had to be used as a proxy. This is not overly restrictive for approximately 80% of international graduate students enter science and engineering fields, and most of the rest go into business fields and economics.

Figures on the skilled workforce (doctoral recipients in science and engineering) came from the Yearbook of Statistics, National Science Foundation Survey of Earned Doctorates. This category includes both domestic and foreign doctoral recipients residing in the United States. For their part, skilled immigrants are defined to include both those coming under H1-B1 visas (both capped and uncapped) and employment-based immigration. This definition is overly broad because, while many of the immigrants permitted under such visas are in technical and managerial fields, there are visa categories for workers in less-skilled occupations. It should be noted that in our data, these employment-based categories do not include accompanying family members, but just the workers themselves.

Data on patents awarded to different institutions, such as universities and industry, were gathered from the National Science Foundation, Science and Engineering Statistics, and from the website of the US Patent and Trademark Office. Figures on research and development expenditures (divided by the GDP deflator), total number of scientists and engineers, recipients of doctoral degrees in S&E, total labor force, and total skilled immigrants entering the country, are available from the Statistical Abstract of the United States, published annually by the US Census Bureau. The GDP deflator and unemployment rate were taken from Economic Report of the President. Simple correlations among the variables in this study are listed in Table 1.

4. Empirical Results

Basic Regressions

Regression results are presented in Table 2 for our basic specifications, estimated in logs of all variables except the Bayh–Dole dummy and the time trend. Reported t-statistics are computed using Newey–West estimated standard errors, which are consistent under unknown serial correlation. Regression (1) lists results for scaled patent applications, while regression (3) lists them for scaled patent grants. Among the standard technical inputs considered, the strongest impact in the equation is exerted by SK, the ratio of total PhD scientists, and engineers in the labor force. In the regressions, SK has an estimated elasticity of 1.22 in applications and 1.82 in patent awards. However, the other technical inputs, scaled real R&D expenditures and the scaled total patent stock, had positive but insignificant coefficients. The reason for this outcome appears to be collinearity between SK, on the one hand, and RD and TOTPATSTOCK, on the other hand. As shown in regressions (2) and (4), when SK is removed both RD and TOTPATSTOCK become significantly positive. Indeed, the coefficient on lagged patent stock is essentially unity in both applications and grants, suggesting that, ceteris
### Table 1. Correlations among Variables

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<th>IPA</th>
<th>IPG</th>
<th>UIPG</th>
<th>OIPG</th>
<th>FOR*</th>
<th>IM*</th>
<th>SK</th>
<th>RD</th>
<th>URD</th>
<th>ORD</th>
<th>TPS5*</th>
<th>TPS7*</th>
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<td>0.59</td>
<td>−0.11</td>
<td>0.39</td>
<td>0.52</td>
<td>−0.17</td>
<td>0.45</td>
<td>0.72</td>
<td>0.44</td>
<td>−0.43</td>
<td>−0.26</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Notes:** IPA is patent applications and IPG is patents granted, both as a proportion of labor force. UIPG and OIPG are patents granted to universities and other institutions, respectively, as a proportion of the labor force. FORGR (FOR* in this table) is foreign graduate students as a proportion of total graduate students. IMCUM (IM* in this table) is the cumulative number of skilled immigrants over a period of six years as a proportion of the labor force. SK is total PhD scientists and engineers as a proportion of the labor force. RD is total real R&D expenditures as a proportion of labor force, while URD and ORD refer to university real R&D and other-institution real R&D, each as a proportion of labor force. TOTPATSTOCK is cumulative patents awarded as a proportion of labor force (TPS5 (TPS7) is TOTPATSTOCK lagged 5 (7) years). BD is the dummy variable for the Bayh–Dole Act.
Table 2. International Students, Skilled Immigration, and Patenting Activity in the United States

<table>
<thead>
<tr>
<th></th>
<th>IPA (1)</th>
<th>IPA (2)</th>
<th>IPG (3)</th>
<th>IPG (4)</th>
<th>UIPG (5)</th>
<th>UIPG (6)</th>
<th>OIPG (7)</th>
<th>OIPG (8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1.46)</td>
<td>(-0.80)</td>
<td>(1.84)**</td>
<td>(-1.34)</td>
<td>(0.67)</td>
<td>(-3.6)**</td>
<td>(1.77)*</td>
<td>(-1.40)</td>
</tr>
<tr>
<td>FORTGR</td>
<td>0.764</td>
<td>1.004</td>
<td>0.572</td>
<td>0.895</td>
<td>0.672</td>
<td>0.506</td>
<td>0.554</td>
<td>0.884</td>
</tr>
<tr>
<td>IMCUM</td>
<td>0.114</td>
<td>0.040</td>
<td>0.048</td>
<td>-0.086</td>
<td>0.134</td>
<td>0.055</td>
<td>0.048</td>
<td>-0.085</td>
</tr>
<tr>
<td></td>
<td>(2.01)**</td>
<td>(0.46)</td>
<td>(0.75)</td>
<td>(-0.79)</td>
<td>(1.93)*</td>
<td>(0.79)</td>
<td>(0.76)</td>
<td>(-0.79)</td>
</tr>
<tr>
<td>SK</td>
<td>1.222</td>
<td>1.820</td>
<td>1.286</td>
<td>1.805</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(3.32)**</td>
<td>(6.04)**</td>
<td>(3.00)**</td>
<td>(6.06)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RD</td>
<td>0.197</td>
<td>0.489</td>
<td>0.091</td>
<td>0.532</td>
<td>-0.052</td>
<td>0.240</td>
<td>(-0.18)</td>
<td>(0.88)</td>
</tr>
<tr>
<td></td>
<td>(1.10)</td>
<td>(2.95)**</td>
<td>(0.48)</td>
<td>(2.57)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>URD</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ORD</td>
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<td></td>
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<td></td>
<td></td>
<td>0.093</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.50)</td>
<td>(2.59)**</td>
</tr>
<tr>
<td>TOTPATSTOCK</td>
<td>0.360</td>
<td>1.020</td>
<td>0.039</td>
<td>0.988</td>
<td>0.331</td>
<td>0.794</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.25)</td>
<td>(4.00)**</td>
<td>(0.26)</td>
<td>(3.19)**</td>
<td>(1.68)*</td>
<td>(7.98)**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UPATSTOCK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.016</td>
<td>0.965</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.11)</td>
<td>(3.12)**</td>
</tr>
<tr>
<td>OPATSTOCK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>0.965</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.11)</td>
<td>(3.12)**</td>
</tr>
<tr>
<td>BD</td>
<td>-0.041</td>
<td>0.116</td>
<td>0.018</td>
<td>0.245</td>
<td>0.090</td>
<td>0.234</td>
<td>0.016</td>
<td>0.241</td>
</tr>
<tr>
<td></td>
<td>(-0.53)</td>
<td>(2.75)**</td>
<td>(0.38)</td>
<td>(2.86)**</td>
<td>(1.21)</td>
<td>(2.14)**</td>
<td>(0.34)</td>
<td>(2.85)**</td>
</tr>
<tr>
<td>TIME</td>
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<td>-0.013</td>
<td>-0.010</td>
<td>-0.015</td>
<td>0.040</td>
<td>0.006</td>
<td>-0.010</td>
<td>-0.015</td>
</tr>
<tr>
<td></td>
<td>(-1.67)*</td>
<td>(-2.47)**</td>
<td>(-1.64)</td>
<td>(-1.69)*</td>
<td>(1.77)*</td>
<td>(0.33)</td>
<td>(-1.74)*</td>
<td>(-1.71)*</td>
</tr>
<tr>
<td>UNEMPLOY</td>
<td>0.007</td>
<td>-0.022</td>
<td>-0.014</td>
<td>-0.040</td>
<td>0.056</td>
<td>0.060</td>
<td>-0.016</td>
<td>-0.044</td>
</tr>
<tr>
<td></td>
<td>(0.09)</td>
<td>(-0.28)</td>
<td>(-0.19)</td>
<td>(-0.39)</td>
<td>(0.38)</td>
<td>(0.34)</td>
<td>(-0.24)</td>
<td>(-0.42)</td>
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<tr>
<td>Observations</td>
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<td>39</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
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<tr>
<td>R-Squared</td>
<td>0.94</td>
<td>0.90</td>
<td>0.87</td>
<td>0.78</td>
<td>0.99</td>
<td>0.99</td>
<td>0.87</td>
<td>0.77</td>
</tr>
<tr>
<td>DW</td>
<td>1.06</td>
<td>1.01</td>
<td>2.33</td>
<td>1.35</td>
<td>2.19</td>
<td>1.94</td>
<td>2.34</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Notes: Variables in the IPA equations are lagged five years (sample 1963–2001), while those in the IPG, UIPG, and OIPG equations are lagged seven years (sample 1965–2001). Figures in parentheses are t-statistics based on Newey–West estimated standard errors and are marked as significantly different from zero at the 1% (***) , 5% (**) and 10% (*) levels.
paribus, there is a dynamic spillover from knowledge to the registration of new ideas. Thus, a powerful “standing on shoulders” effect persists in the data.

Turning to the issue of central concern here, increases in foreign graduate students as a proportion of total graduate students (FORTGR) had a significantly positive impact on both applications and awards. The estimated elasticities in the applications equations range between 0.76 and 1.00, while in the grants equations they range between 0.57 and 0.89. These strongly positive impacts are robust to the exclusion of SK. The presence of skilled immigration, cumulated over six years (IMCUM), is estimated to increase patent applications with an elasticity of 0.114, and to have a smaller impact on patent grants. However, the significance of this variable disappears when SK is removed from the regressions. It is interesting that the sensitivity of patent activity, with respect to foreign graduate students, is considerably larger than that with respect to skilled immigration. This result strongly supports the view that the presence of foreign students in the United States is pro-innovation in relation to overall graduate enrollment.

Implementation of the Bayh–Dole Act had a detectably positive impact on lagged total patent applications in equation (2) and grants in equation (4), where SK is removed. The time trend seemed to have a slightly negative effect on both applications and grants, suggesting at least that the specifications have corrected for upward trends in the data. Finally, the unemployment rate had no detectable effects on patent applications or grants.\textsuperscript{18}

Equations (5) and (6) contain the results for university patent grants, while equations (7) and (8) pertain to patent grants made to non-university institutions. Of interest here, is whether there are detectable differences in behavior between patent grants to universities and patent grants to non-university actors. The lagged patent stock was positive and highly significant in university equation (6), with an elasticity estimate of around 0.79. Similarly, when SK is removed in equation (8), the impact of lagged patents on other-institution awards is significant, at 0.97. These results suggest that inherited knowledge has positive influence on innovation by both universities and other organizations. The implementation of the Bayh–Dole Act appears to have induced significantly more patent grants to both university researchers and to those in other institutions.

It is of interest to put the elasticities on foreign graduate students in perspective, by computing the implied impacts on patent levels from a change in enrollments. Computed at sample means, a 10% rise in the ratio of foreign graduate students to total graduate students (FORTGR), holding total graduate students constant, would imply an increase in foreign students of 7726. Applying the estimated elasticity of 0.76 from regression (1) to the mean of the ratio of patent applications to labor force (IPA), holding constant the labor force, there would be an increase in later applications of 6793 (or around 4.5% of mean total applications of 151,469). Thus, we compute a marginal impact of another foreign graduate student to be around 0.88 patent applications throughout the economy. Turning to total patent grants, using the coefficient from regression (3), a 10% rise in the ratio FORTGR would expand later patent grants by 4616 (or around 5.1% of mean total grants), suggesting a marginal productivity of 0.57 grants economy-wide. These are large figures in the context of US patent flows.\textsuperscript{19}

Turning to the breakdown into university and non-university awards, consider the coefficients on FORTGR in regressions (5) and (7). Our calculations find that a 10% rise in the ratio of foreign graduate students would generate another 73 university grants (an increase of 6.8% of mean total grants of 1068) and another 4448 private (non-university) patent grants (an increase of 5.0%).\textsuperscript{20} It is evident that the enrollment of foreign graduate students ultimately generates more non-university patent awards,
the number of which is far larger than university grants in any case, which may happen through a variety of channels.

We can compute similar impacts from skilled immigration, using the corresponding coefficients on IMCUM in Table 2. We do this for regressions (1) and (5), where the coefficients are significantly positive. These calculations find that a 10% rise in the six-year cumulated number of skilled immigrants would increase later patent applications by 1187 (0.8% of sample mean) and university grants by 10 (0.9%). It seems from these computations that skilled immigration has considerably smaller impacts on patenting activity than does enrollment of foreign graduate students.

In Table 3, we present results of a slightly different specification. It can be argued that the input aggregate in equation (2) is incorrect, for it implies that the total R&D input
(H) would be zero in the event that the enrollment of foreign graduate students were zero. In turn, there would be no ideas generated in the production function (1). An alternative logic would be that there is a basic level of productivity that exists in the absence of foreign graduate students, generated by the other inputs. Accordingly, we re-estimate each model, taking the input FORTGR to be log(1 + foreign graduate student share), while other variables are held the same. As may be seen by comparing equation (9) in Table 3 with equation (1) in Table 2, the impact of foreign graduate students remains strongly positive and significant, and the other coefficients are not much affected. The elasticity of 8.56 on the adjusted foreign graduate share implies a somewhat larger percentage increase in lagged patent applications from a 10% rise in those students, holding total graduate enrollments constant. Specifically, this coefficient implies a rise in applications of 7.6%, or 11,152 applications. The impacts of estimating this specification on the other patent flows are similar. The elasticities of both total patent grants and other patents grants imply a marginally larger effect of foreign enrollments on those awards, compared to Table 2, while that of university patent grants indicates a substantially larger percentage impact.

While these figures suggest that increasing the number of foreign graduate students raises US patent applications and grants, they cannot easily be translated into impacts on US income or GDP. It is not possible to find information on licensing revenues generated by the patents awarded in our sample, which would be the appropriate measure of income generated. Nor is it possible to determine how much employment or wage income was supported by these patents. However, a recent study by Bessen (2006) offers an alternative approach, which is to calculate the mean and median values of patents granted in the United States from 1985 to 1991. These values may be inferred from decisions of firms to renew them and pay required renewal fees. A low-valued patent would not be renewed, while higher-valued patents would be renewed multiple times despite rising fees. In the United States, such fees must be paid every four years of the patent to keep it in force. Using an ordered-probit model, Bessen found a mean present value of patents of $78,168 and a median present value of $7175 in 1992 dollars. The difference in mean and median values, reflects the fact that a small number of patents achieve considerable market success, while most earn relatively little.

We may apply the mean value to our earlier calculations to determine, at least roughly, how much enrollments of additional graduate students contributed to economic value through patents granted in the United States during our time period. There are two ways to make this computation. A conservative approach is based on our evidence that, at the sample means, a 10% rise in the ratio of foreign graduate students to total graduate students would generate 4616 additional patent grants. Evaluating these at the average patent value, such a rise would imply an aggregate wealth gain of $360.8 million per 10% increase. Over our period of 1965 to 2001, this ratio rose by 64%. This suggests that the increase in foreign enrollments generated additional patent value in the United States of approximately $2.31 billion from 1965 to 2001.

A second, and less conservative, calculation is based on assuming that the marginal productivity of a foreign graduate student, estimated to be 0.57 patent grants, held throughout the period. Applying the mean value, we compute a marginal wealth gain of $44,556 in 1992 dollars. In the aggregate, foreign enrollments rose by 185,100 students from 1965 to 2001, implying a rise in patents awarded of 105,507 and an overall wealth gain of approximately $8.24 billion.

It is difficult to compute a benefit-cost ratio for foreign enrollments based on such figures. It is true that international students are expensive to educate, with costs over a five- to six-year training period, perhaps exceeding $44,556 per student. Furthermore,
these students also contribute to teaching and the generation of research publications in addition to patents, suggesting that their marginal revenue products are higher than that. They also contribute to innovation beyond graduate school, a factor deserving close study. On the basis of our results, however, a fair claim is that far fewer patents would have been generated in the absence of international students, reducing aggregate patent wealth. Moreover, these gains in patent rents offer a substantial offset to the slightly negative aggregate impact of foreign graduate students reported in Borjas (2002).25

Cointegration Analysis

While the econometric results seem robust, there is a danger that the regression coefficients are spuriously significant, because they are based on aggregated time-series data. It is conceivable that both the ratio of foreign graduate students to total graduate students and the ratio of patent applications (or grants) to the labor force, are both driven upward over time by uncontrolled factors, without a causal relationship.

To consider this issue, we turn to standard cointegration analysis. Note from Table 2 that the data may well be serially correlated, with the Durbin–Watson statistic being less than 1.35 in four of the eight equations. Thus, the initial task is to investigate each of the time-series variables for unit roots, which we have done with the augmented Dickey–Fuller test. That test found that IPA, IPG, UIPG, OIPG, FORTGR, SK, RD, ORD, TOPATSTOCK, UPATSTOCK, OPATSTOCK, and UNEMP, are integrated of order one, while IMCUM and URD are integrated of order 2. Thus, despite the scaling of the data there remain concerns about stationarity of our series.

We undertake, therefore, estimation of long-run cointegrating equations using the Johansen (1988) method, and assuming all variables are integrated of order one.26 To limit the dimensionality of the problem, we consider only TOPATSTOCK as the measure of past ideas, setting aside UPATSTOCK and OPATSTOCK.27 Listed in Table 4 are the estimated long-run cointegrating equations for each dependent variable. The relationships are estimated with the same set of variables as in Table 2, permitting a linear trend in the data, and both an intercept and trend in the cointegrating relationship. Note that the fact that the Johansen procedure finds the existence of a cointegrating equation in each case, supports the claim that there is a long-run relationship among our set of variables, implying that the least-squares coefficients in Table 2 are estimated consistently.

In Table 4, we report only those results for the broadest specifications, retaining SK in each case, and do not report the intercept. Standard errors are listed in parentheses. Looking at all equations, both the proportion of foreign graduate students (FORTGR) and the share of doctoral scientists and engineers in the labor force (SK), have coefficients that are positive and highly significant. The estimated long-run elasticity of scaled patent applications (IPA) to an increase in the ratio of foreign graduate students to total graduate students is 0.28, suggesting that the estimate of 0.76 in equation (1), Table 2, was somewhat high and that the actual relationship is somewhere between these estimates. In the patent grants equations, the coefficients on FORTGR are somewhat higher in Table 4 than in Table 2 for total and other grants, but lower for university grants. However, in all cases the elasticity is positive and significant.28

The impact of highly skilled technical workers (SK) is now estimated to be over twice that in the original regression for patent applications. The coefficients in the total and other patent grants equations are similar to those in the least-squares results, but estimated to be considerably higher for university grants. All patenting activity is highly
elastic with respect to technical skills in the long run. As for skilled immigrants, the coefficients are generally insignificant, consistent with the findings in Table 2.29

The surprising finding in Table 4, however, is that the coefficients on R&D expenditure, lagged patent stock, and the Bayh–Dole dummy often turn negative in the cointegration analysis, though R&D remains significantly positive in the total and other patent grants equations. This result most likely reflects the fact that estimating the vector autoregression in the Johansen procedure places considerable stress on the coefficients when there is collinearity among the technical input variables and a relatively short time series. Under such circumstances, primary focus should be placed on the least-squares estimates in Table 2, which are consistent and suggest positive relationships between patent activity, on the one hand, and patent stocks and the Bayh–Dole dummy, on the other.

The remarkable aspect of the results in Table 4 is that the impact of the relative presence of foreign graduate students remains positive and significant throughout all specifications. The coefficients on technical skills (SK) also remain highly significant and elastic throughout. Overall, these results suggest that the role of relative enrollments of foreign graduate students in stimulating US innovation, as measured by future patent grants and awards, is not spurious.

5. Concluding Remarks

In this paper, we provide systematic evidence that the presence of foreign graduate students has a positive and significant effect on American innovation, as measured by
patent applications and grants. To summarize, larger enrollments of international graduate students, as a proportion of total graduate students, result in a significant increase in patents awarded to both university and non-university institutions, as well as increases in total patent applications. This finding points out the importance of scientific contributions made by international graduate students in both settings.

There are two likely reasons for this result beyond the direct impact of foreign graduate students on university innovation. First, research by foreign graduate students is likely to affect patenting by non-university institutions, due to increasing collaboration between the academic and non-academic groups. Second, industries may purchase the intellectual property rights of any discovery from the innovating university and, hence, benefit indirectly from international student contributions (Laursen and Salter, 2004).

The results indicate indirectly that the United States gains from trade in graduate education services beyond tuition payments. Relatively open access to international students has allowed US universities to enroll capable graduate students in S&E from abroad. In turn, international graduate students contribute to innovation and patenting. Presumably, this is because international graduate students are relatively concentrated in S&E fields. Indeed, in a number of highly ranked engineering schools, international students account for nearly 80% of doctoral students (Laursen and Salter, 2004). Further, because of work restrictions for international students, domestic students have greater opportunities to be employed in non-research activities in both university and non-university institutions. Hence, it is not surprising that the presence of international students, along with skilled immigrants, and including international faculty, exchange visitors, research fellows and post-doctoral research associates, is a significant factor behind increases in innovation and patenting at universities.

References


———, “Do Foreign Students Crowd out Native Students from Graduate Programs?” in Ronald G. Ehrenberg and Paula E. Stephan (eds), Science and University, Madison, WI: University of Wisconsin Press (2005a).


Stephan, Paula, Grant Black, and Shiferaw Gurmu, “The Role of Foreign-born Graduate Students in University Patenting,” Atlanta, GA: Georgia State University manuscript (2005).


Notes

1. Recently, a letter to this effect was published by a broad coalition of US academics representing 25 organizations and 95 individuals. See “Academics Warn of Crisis over Visa Curbs,” Financial Times May 16, 2004.


4. See, for example, National Governors Association, “The High School Crisis and America’s Economic Competitiveness to be Discussed,” September 29, 2003, at http://www.nga.org/nga/newsRoom/1,1169,CPRESS_RELEASE%5ED_5948,00.html

5. For comparison with other countries, see the results of the Trends in International Mathematics and Science Study (TIMSS) at http://timss.bc.edu/timss2003.html.


8. Skilled immigrants are defined to include both those coming under H1-B1 visas and employment-based immigration. Data sources include Freeman et al. (2004); Statistical Abstract of the United States (various years); Institute for International Education, Open Doors (various years); and Department of Homeland Security, US Immigration Statistics.
11. These data are from the National Science Foundation and may be found at http://www.nsf.gov/sbe/srs/seind02/append/c5/at05-24.xls
13. That paper was written as a comment on an earlier version of our analysis in this paper.
14. Note in particular that we do not include the period after September 11, 2001.
15. See various issues of *Open Doors*.
16. It should be noted that, because some foreign-born doctoral recipients enter under skill-based visas, they are counted in both SK and IMCUM, however this overlap is small.
17. The results reported involve five-year lags for patent applications and seven-year lags for patent awards. We experimented also with different lag structures, which tended to reduce the significance of some coefficients, but did not change the results materially. Results are available on request.
18. The equations were estimated also without the unemployment rate, with virtually no difference in results.
19. These figures are calculated at means across the entire sample. If these elasticities were applied to the far-higher average patent numbers in the late 1990s, the corresponding predicted increases in innovative activity would be larger.
20. In principle, the increases in UIPG and OIPG should sum to the growth in total patent grants, but does not do so here, because this adding-up constraint was not imposed in the estimation.
21. We are grateful to a referee for making this point.
22. We also estimated all equations with the same transformation applied to FORTGR, IMCUM, SK, and the PATSTOCK variables. This fuller specification reduced the estimated elasticities on the ratio of foreign graduate students in total enrollments compared to Table 3, though they remain highly significant, and implies impacts on patenting activity that are little changed from those in Table 2. Regressions are available on request.
23. Some might argue for using the median value but, since we use the full population of patent grants in our analysis, the average value should be the appropriate factor.
24. It is worth noting that there is an increasing tendency for the costs of US graduate education in S&E to be funded by domestic and foreign corporations. Examples may be found at the University of Michigan (see http://www.corporaterelations.umich.edu/partners.htm) and Clemson University (see http://www.clemson.edu/centers/brooks/news/BMW.pdf). To the extent such funding is foreign-sourced, the net US cost per student is reduced.
25. It would be interesting to consider the effects of the small outward flows of US students to foreign universities. To the extent that they are pushed abroad because domestic universities substitute foreign students, which is doubtful given the results in Card (2005), there could be some reduction in patents generated in the United States, though a net positive effect from the rising foreign share. Note also that few other countries permitted university patenting until recently.
26. The assumption of a common order of integration is standard, when there are few variables exhibiting higher-order integration. The failure to reject a 2d-order integrated process for IMCUM and URD, likely reflects the low power of the augmented Dickey–Fuller test with a relatively short time series.
27. When UPATSTOCK and OPATSTOCK are replaced by TOTPATSTOCK in regressions (5)–(8) in Table 2, the results are quite similar, suggesting that this replacement is valid.
28. These qualitative findings hold also for cointegrating equations applied to the specifications in Table 3, which are suppressed here to conserve space.
29. Recall that the employment-based categories include some lower-skilled occupations, so this result may not be unexpected.