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THE CONTRIBUTION OF SKILLED IMMIGRATION AND

INTERNATIONAL GRADUATE STUDENTS TO U.S. INNOVATION

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ABSTRACT

The impact of international students and skilled immigration in the United States on innovative activity is estimated using a model of idea generation. In the main specification a system of three equations is estimated, where dependent variables are total patent applications, patents awarded to U.S. universities, and patents awarded to other U.S. entities, each scaled by the domestic labor force. Results indicate that both international graduate students and skilled immigrants have a significant and positive impact on future patent applications as well as on future patents awarded to university and non-university institutions. Our central estimates suggest that a ten-percent increase in the number of foreign graduate students would raise patent applications by 4.7 percent, university patent grants by 5.3 percent and non-university patent grants by 6.7 percent. Thus, reductions in foreign graduate students from visa restrictions could significantly reduce U.S. innovative activity. Increases in skilled immigration also have a positive, but smaller, impact on patenting.

Key Words: Innovation, Foreign Graduate Students, U.S. Immigration, Patenting

JEL Codes: I2, J6, O3

1. Introduction

Since the advent of far tighter restrictions on the issuance of U.S. education visas in the wake of the attacks of September 11, 2001, immigration policy for foreign graduate students has become the subject of intense debate. Those who are concerned about the policy shift claim that it will harm the nation's innovation capacity. For example, American university officials are increasingly concerned that these restrictions could cause "…a crisis in research and scholarship…"[1] The same point finds its way into editorials.[2] Lawrence Summers, president of Harvard, warned the U.S. State Department that the decline in foreign students threatens the quality of research coming from U.S. universities,[3] although this claim has been disputed by a prominent analyst (Borjas, 2002, 2004).

If limits and delays in the number of foreign graduate students in science and engineering 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 technology (Basu et al., 2001; Basu, et al, 2003; Gordon, 2004a, 2004b). 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 U.S. industries and universities (Kortum, 1997; Hall, 2004).

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[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.

[2] "Visas and Science: Short-Sighted," *The Economist*, May 8, 2004.

"Security Restrictions Lead Foreign Students to Snub US Universities," *Nature,* September 15, 2004.

[3] *Financial Times*, April 28, 2004.

The United States remains at the cutting edge of technology despite frequent complaints about quality deficiencies in its secondary education system.[4] 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.[5] What may reconcile these factors is that the United States attracts large numbers of skilled immigrants that enter directly into such technical fields as medicine, engineering, and software design (Gordon, 2004c). Moreover, the education gap is filled by well-trained international graduate students and skilled immigrants from such countries as India, China, Korea, and Singapore (the last two of which rank at the top in mathematics and science achievement). Certainly 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 and skilled immigrants are important inputs into the U.S. capacity for continued innovation, but this basic hypothesis surprisingly has not been formally tested. In this paper we estimate an innovation production function in which graduate students and skilled immigrants are an input into the development of new ideas, both at universities and in the private sector. The econometric model permits productivity differentiation between domestic and foreign graduate students and domestic and foreign skilled workers in producing patents awarded to universities and private businesses.

Results of the econometric analysis indicate that, holding constant the presence of total graduate students and the cumulative number of doctorates in science and

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

engineering, increases in the presence of foreign graduate students have a positive and significant impact on future U.S. patent applications and grants awarded to both firms and universities. This finding extends to the relative presence of skilled immigrants in the labor force, with an increase in the skilled immigrant share significantly raising later patent awards in both types of institutions. Put simply, we find that both enrollment of foreign graduate students and immigration of skilled workers 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 Three we develop a simple model and set out the econometric specification. In Section Four we provide results and discuss their economic and policy significance. In Section Five we conclude.

2. Background and Literature Review

The question of whether skilled and other forms of immigration bring net benefits is much discussed in media and policy circles in rich countries.[6] It is even the subject of negative, and rather polemical, pieces by well known scholars (Borjas, 2002, 2004; Huntington, 2004). It is evident that a major component of such gains must be the contribution of skilled immigrants and 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.

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[5] For comparison with other countries see the results of the Trends in International Mathematics and Science Study (TIMMS) at http://timss.bc.edu/timss2003.html.
[6] See, for example, "The Politics of Immigration: Business v. Bush," *The Economist*, October 18-24, 2003, pp. 29-30, and "German Immigration: Brains Not Welcome Here," *The Economist*, May 1-7, 2004, p. 50.

2a. 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 U.S. immigrants in recent decades, could reduce the wages of domestic unskilled labor and contribute to rising wage inequality (Clark, et al, 2002).[7]

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 this analysis is misleading because it fails 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 generate dynamic gains through increasing innovation. Such innovation could contribute to future productivity gains of native workers, resulting in a net increase in real wages. Put differently, in a dynamic context immigration of skilled workers would be complementary to local skills, rather than substitutes for them. Thus, more realistic theory suggests that skilled migration would

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[7] In fact, Borjas, et al (1997) found that immigration into the United States during 1980-95 accounted for about 25 to 50 percent of the decline in the relative wage of high-school dropouts. They suggested that unskilled immigration had relatively little positive impact on skilled-labor wages.

support rising aggregate real incomes in the long run.[8] Ultimately, the impacts of immigration 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 engineering and science students.[9] Thus, an essential motivation for our paper is to investigate whether this support is rooted in the dynamic innovation impacts of such foreign workers studying and residing in the United States.

2b. Foreign Graduate Students and Skilled Immigration

The issue of international students and their contribution to host-country economies has been addressed only recently although students have been leaving their home countries for study abroad for nearly four thousand years (Cohen, 2001). Until World War II, a substantial proportion of international students studied in Europe, but this began to change after 1945. Most pronounced was the dramatic shift by Asian students since 1985 toward study in the United States.

To put the U.S. situation into context, note that annual flows of skilled immigrants 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.[10] An important impetus was the Hart-Cellar Immigration Act of 1965, which removed the National Origins quotas established by the Johnson-Reid

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[8] See also Chander and Thangavelu (2004), who show in a theoretical model that permitting high-skilled immigration plus offering education subsidies is sufficient to ensure new technology adoption.
[9] See "The Politics of Immigration" above note 6.
[10] 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, *U.S. Immigration Statistics*.

Immigration Act of 1924, 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), Clark, et al (2002) and Antecol et al. (2003) indicate that legislative reforms resulted in a sharp increase in the flow of highly talented international workers into the United States. Further, there is an important relationship between human capital investment and immigration (Duleep and Regets, 1999).

Data demonstrate further that the number of skilled immigrants as a proportion of the U.S. 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, and those who are educated in the United States earn higher wages (Bratsberg and Ragan, 2005; Schoeni, 1997). Aslanbeigui and Montecinos (1998) found that 45 percent of international students from developing countries planned to enter the U.S. labor market for a time and 15 percent planned to stay permanently. Another 15 percent planned to go to a third country. Despite attempts by the U.S. Congress to forbid employment of international students after graduation since the early 1980s,[11] and in some cases restrict the flow of international students to domestic universities,[12] the United States still allows a significant proportion to stay and work after graduation and in a majority of cases even

[11] In 1982 and again in 1984 legislation sponsored by Senator Simpson and Representative Mazzoli forbidding the employment in the United States of international graduates of U.S. universities passed both chambers of Congress before dying in the Conference Committee. In 1995 Senator Simpson and Representative Lamar Smith unsuccessfully resurrected the proposal.

[12] Senator Feinstein tried to put a moratorium on all international students soon after the September 11, 2001 attack. The proposal was shelved after protests from U.S. universities. Representative Rohrbacher has proposed that U.S. universities replace international students with domestic students although the latter may be less qualified.

grants them permanent residence. Thus, graduate training of foreign students may have long-lasting impacts on innovation capacities.

On a negative note, Borjas (2002) speculates that foreign students in the United States benefit the economy to the tune of $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 (2004) finds a strong negative correlation between the enrollment of native men in U.S. graduate programs and the enrollment of foreign students. Institutions which experienced the largest increase in foreign enrollment were also institutions that experienced the steepest fall in the enrollment of native males.

For our purposes the interesting aspect of this claim is that Borjas seems to suggest that domestic and foreign graduate students are highly substitutable and display similar characteristics. In fact, 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 TIMMS and other international tests indicate that the native U.S. student pool for engineering and science programs is likely to be limited due to lower math and science achievement.[13] This suggests that student populations are not readily substitutable and that university technical training programs may have increased their demand for foreign students.

As a result it is not surprising that a recent study indicates that there has been a sharp drop in the proportion of PhDs in science and engineering awarded to U.S.-born males between the early 1970s and 2000 (Freeman et al., 2004). In 1966 these students accounted for 71 percent of science and engineering PhD graduates, while six percent

were awarded to U.S.-born females and only 23 percent of doctoral recipients were foreign-born. The situation was reversed by 2000, when only 36 percent of doctoral recipients were U.S.-born males, 25 percent were U.S.-born females and 39 percent were foreign-born. Contradicting Borjas (2004), the authors found that foreign students were not substituted for domestic students. The number of PhDs granted to undergraduates from U.S. institutions, most of whom were U.S. citizens, did not change much during this period, while there was substantial growth in the number of foreign bachelor's graduates obtaining U.S. doctorates. Thus the change in proportion is mostly due to the expansion of PhD programs, with a majority of the new slots being taken by foreign students rather than through substitution.

These same trends explain the fact that the proportion of foreign-born faculty with U.S. doctoral degrees at U.S. universities has gone up sharply during the past three decades, from 11.7 percent in 1973 to 20.4 percent in 1999. For engineering it rose from 18.6 percent to 34.7 percent in the same period.[14]

In the last few years, however, there has been a steep decline in foreign student applications for admission into U.S. universities and a corresponding increase in applicants to universities in Asia, Australia and New Zealand.[15] This is due both to difficulties in obtaining U.S. visas since 9/11 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). Recent evidence also suggests that collaboration between foreign and US universities has shown marked increase during the past two decades and increasingly research activities are being "dispersed" abroad, particularly to

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[13] http://nces.ed.gov/pubs99/1999081.pdf
[14] http://www.nsf.gov/sbe/srs/seind02/append/c5/at05-24.xls

Asian countries, partly to take advantage of complementary capabilities (Adams et al., 2004). Modern communication technologies and cuts in public funding presumably have contributed to this trend, and it is likely that if qualified students become increasingly unavailable in the United States the tendency will accelerate.

2c. University Research and Patenting

In the United States, patenting of new inventions by universities began to accelerate during the 1960s, although such institutions as Stanford had been innovating and attempting to patent inventions from the early 1920s (Etzkowitz, 2003; Henderson and Jaffe, 1998). University innovation and patenting were significantly boosted by the Bayh-Dole Act of 1980, which allowed U.S. universities to commercialize research results (Sampat et al., 2003; Mowery et al., 2001). Currently the determinants of university patenting in the United States and its implications for the economy are a central subject for inquiry (Lee, 1996; Thursby and Kemp, 2002; Jensen and Thursby, 2001; Thursby and Thursby, 2000; Owen-Smith and Powell, 2003).

National governments typically play a significant role in financing research that supports patenting. Furthermore, there is also considerable university-industry collaboration, especially in the United States, with a significant proportion of research funding coming from industries (Cohen et al., 1994; Dasgupta and David, 2002; Agrawal and Cockburn, 2003; Link and Scott, 2003; Laursen and Salter, 2004). Indeed, U.S. state and federal budget cuts have created a vacuum in research financing that is increasingly being filled by both domestic and international corporations (Beath et al., 2003). For

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[15] http://smh.com.au/articles/2004/07/14/1089694426317.html?from=moreStories&oneclick=true

example, recently BMW set up a fund to finance most of the research of the Automotive Engineering Department at Clemson University in South Carolina.[16]

As noted earlier, prior studies of university patenting have not analyzed the role of skilled immigrants or foreign graduate students as inputs into the innovation production function. 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. Hence, they must rely on skilled immigration and foreign talent to augment their skills. Recent experience indicates that countries such as the United States, Australia, Singapore, and more recently, People's Republic of China, which have been relatively open to foreign talent, have experienced faster rates of economic growth than such countries as Germany, Japan and Korea, where opposition to any form of foreign talent is significant. Thus, it seems plausible from this experience that a relatively open-door 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 U.S. innovation, we modify the "national ideas production function" that is widely used in innovation studies (Stern, et al, 2000; Porter and Stern, 2000). This may be written in general form as

$$\dot{A}_t = \boldsymbol{d} H_{A,t}^{l} A_t^{f} \tag{1}$$

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[16] http://www.clemson.edu/centers/brooks/news/BMW.pdf

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 (λ), the stock of ideas already in existence (A_t) and the ability of that stock to support new invention (ϕ). 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 U.S.-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, 1984). 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, 2000). First, patents do reflect an important portion 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.

$$H_{A,t}^1 = H_{F,t}^{1_F} H_{G,t}^{1_G} H_{I,t}^{1_I} H_{S,t}^{1_S} H_{R,t}^{1_R} \qquad (2)$$

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. It should be noted 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 **d** 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 **d** to be a function of time (capturing changes in U.S. ideas productivity) and key

policy changes. The primary policy we consider is passage of the Bayh-Dole Act in

1980, which should have changed the ability of universities (and perhaps enterprises also)

to convert technical inputs into new ideas.

To implement this structure econometrically, we must account for several other

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., 2003).

The exact times for applications and awards vary according to the field. For

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pharmaceuticals it could take as long as fifteen years for patent applications, due to the lengthy period for clinical trials, 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. 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 relevant period the absolute numbers of foreign students have increased steadily, as have patent applications. 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.

Third, we employ a log-linear approximation of equation (1) in the estimation. Finally, we estimate equations capturing the determinants of total patents, university patents, and patents issued to other entities. Because the error terms associated with these equations are likely to be correlated our estimation technique is seemingly unrelated regression.

Putting these ideas together yields two specifications. Our basic econometric specification is as follows.

$$IPA_{t+5} = \alpha_1 + \lambda_{Fl}FORTGR_t + ?_{T1}TOTGR + \lambda_{I1}IMCUM_t + \lambda_{Sl}SK_t + \lambda_{Rl}RD_t +$$

$$\phi_{1t}TOTPATSTOCK_t + \delta_{B1}BD + \boldsymbol{q}_{1t}TIME_t + \eta_{1t}$$

$$\text{IPG}_{t+7} = \alpha_2 + \lambda_{F2}\text{FORTGR}_t + ?_{T2}\text{TOTGR} + \lambda_{I2}\text{IMCUM}_t + \lambda_{S2}\text{SK}_t + \lambda_{R2}\text{RD}_t +$$

$$\phi_{2t}\text{TOTPATSTOCK}_t + \delta_{B2}\text{BD} + \boldsymbol{q}_{2t}\text{TIME}_t + \eta_{2t}$$

In the first equation the dependent variable is total patent applications as a percentage of the U.S. labor force, five years after inputs are employed. These inputs include foreign graduate students as a percentage of total graduate students (FORTGR), total graduate students as a proportion of labor force (TOTGR), skilled immigrants as a proportion of labor force (IMCUM), PhD's employed in science and engineering as a percentage of labor force (SK), and real research and development expenditures as a percentage of labor force (RD). We employ both FORTGR and TOTGR to permit identification of the impact of foreign graduate students, holding constant the total relative presence of graduate students in U.S. 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. In both equations we anticipate the coefficients on all explanatory variables to be positive.

Note that this first specification does not distinguish between university and non-university patenting activity because data from the U.S. 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:

$$IPA_{t+5} = \alpha_1 + \lambda_{F1}FORTGR_t + \lambda_{G1}TOTGR_t + \lambda_{I1}IMCUM_t + \lambda_{S1}SK_t + \lambda_{R1}RD_t +$$

$$\phi_1 TOTPATSTOCK_t + \delta_{B1}BD + \boldsymbol{q}_{1t} TIME_t + \eta_{1t}$$

$$UIPG_{t+7} = \alpha_2 + \lambda_{F2}FORTGR_t + \lambda_{G2}TOTGR_t + \lambda_{I2}IMCUM_t + \lambda_{S2}SK_t + \lambda_{R2}URD_t +$$

$$\phi_{U2} UPATSTOCK_t + \phi_{O2} OPATSTOCK_t + \delta_{B2}BD + \boldsymbol{q}_{2t} TIME_t + \eta_{2t}$$

$$OIPG_{t+7} = \alpha_3 + \lambda_{F3}FORTGR_t + \lambda_{G3}TOTGR_t + \lambda_{I3}IMCUM_t + \lambda_{S3}SK_t + \lambda_{R3}ORD_t +$$

$$\phi_{U3} UPATSTOCK_t + \phi_{O3} OPATSTOCK_t + + \delta_{B3}BD + \boldsymbol{q}_{3t} TIME_t + \eta_{3t}$$

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, cumulative university and non-university patent stocks during the past seven years (UPATSTOCK and OPATSTOCK), all divided by labor force, and the dummy variable for the Bayh-Dole act. The third equation captures non-university patents awarded (OIPG) after a seven-year lag. It incorporates non-university real R&D (ORD)

expenditures, cumulative university and non-university patent stocks (UPATSTOCK and OPATSTOCK), and the Bayh-Dole dummy.

Again, all 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 patents awarded as a proportion of labor force should be positively affected by the Bayh-Dole Act of 1980, which gave the universities considerable leeway in research and patenting. Both university and non-university patents should be positively affected by their lagged own-patent stock. However, because there is likely to be learning by each group from the ideas protected by patents owned by the other, we anticipate a spillover impact measured by the coefficients on UPATSTOCK (in the non-university equation) and OPATSTOCK (in the university equation).

In addition to these basic specifications, we incorporate into supplementary equations a variable SEDOCCUM, which is the number of doctorates awarded by U.S. universities in all areas of science and engineering, excluding social sciences, cumulated over the prior five years, again scaled by the labor force. The notion here is that, controlling both for total graduate students and the share of foreign graduate students, the number of successful finishers in science and engineering could provide further impetus to inventive activity in the United States. By cumulating these graduates over the prior five years we actually capture the presence of ultimately successful students in the cohorts entering graduate school from ten to five years before patent registration.

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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 U.S. unemployment rate lagged in the same way as other independent variables.

These econometric models are implemented with annual data over the period 1965 to 2001.[17] The data were collected from a variety of sources. Figures on U.S. graduate students were gathered from the U.S. Department of Education *Statistical Quarterly*. No separate data were available on the number of U.S. graduate student enrollment in science and engineering 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 science and engineering 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 percent of international graduate students enter science and engineering fields and most of the rest go into business fields and economics.[18]

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 U.S. 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 science and engineering, total

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[17] Note in particular that we do not include the period after September 11, 2001. Our intent is to discover whether foreign students and skilled immigration could account for increases in technical productivity prior to that period, which may inform policy discussions in the ensuing era.

[18] See various issues of *Open Doors*.

labor force, total number of international students and total skilled immigrants entering the country are available from the *Statistical Abstract of the United States* published annually by the U.S. Census Bureau. The GDP deflator and unemployment rate were taken from *Economic Report of the President*. Skilled immigrants are defined to include both those coming under H1-B1 visas (both capped and uncapped) and employment-based immigration. It should be noted that in our data these categories do not include accompanying family members, but just the workers themselves. Simple correlations among the variables in this study are listed in Table 1.

4. Empirical Results

Regression results for total patent applications and grants as a proportion of labor force are presented in Table 2 for our basic specifications. [19]   Note in the first two columns that the share of total graduate students in the labor force had no detectable impact on lagged patent applications or grants. Thus, we also estimate specifications (3) and (4), which exclude this variable. It may be seen that lagged patent stock as a proportion of labor force had a significant and positive impact on patent applications in regressions (1) and (3). However, its impact on patent grants was insignificant in the full specification in regression (2) and marginally significant in regression (3). The elasticity of patent applications with respect to increases in cumulative knowledge is estimated at around 0.53. This result suggests that, *ceteris paribus*, there is a dynamic spillover from knowledge to the registration of new ideas, confirming the "standing on shoulders" idea.

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[19] 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.

Both of our measures of technical personnel in the U.S. labor force, SEDOCCUM and SK, are estimated to have significantly positive effects on innovation as measured through patents. For example, SK (scientists and engineers in the labor force) had a powerful and positive impact on measured innovation, with an elasticity of between 0.75 and 0.98. These coefficients are robust despite the inclusion of SEDOCCUM (the cumulative number of doctorates earned in engineering and science), which is highly correlated with SK (see Table 1). The estimated elasticity of grants with respect to SEDOCCUM is over twice that of the elasticity of applications. In contrast, the coefficients on real R&D spending were not significantly different from zero, except in specification (2). This seems largely because of collinearity between RD and SEDOCCUM.[20]

Turning to the issues of central concern here, the presence of skilled immigration, cumulated over six years (IMCUM), is estimated to increase patent applications (after five years) with an elasticity of 0.07 and to have a slightly larger impact on patent grants (after seven years). Further, increases in foreign graduate students as a proportion of total graduate students had a significantly positive impact on both applications and awards, with elasticities ranging between 0.47 and 0.73. It is interesting that the sensitivity of patent activity with respect to foreign graduate students is more than four times larger than that with respect to skilled immigration. This result strongly supports the view that the presence of foreign students and skills in the United States is pro-innovation in relation to overall graduate enrollment.

Implementation of the Bayh-Dole Act had positive and significant impacts on later patent applications and grants in the both sets of equations. There was no

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[20] When these specifications are estimated without SEDOCCUM, the impact of RD is significantly positive.

suggestion of a significant residual time trend in applications, though the coefficients were negative in the grants equations. Finally, the unemployment rate had no detectable effects on lagged patent applications or grants.[21]

In Table 3 the regressions are broken down into total patent applications, university patent grants, and other patent grants, using the SUR technique. The coefficients for the patent applications equations are quite similar to those in Table 2, as expected, and require no further discussion. 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 stocks were significantly positive only in the university equations, with an elasticity estimate of around 0.44 to 0.57. This suggests that inherited knowledge has a more powerful influence on innovation by universities than by other organizations. It is also noteworthy that the lagged university patent stock was estimated to have a small positive spillover impact on non-university patent grants. In contrast, lagged R&D expenditures had strongly positive effects on patent grants by other institutions, but not by universities. Again, this is due partly to collinearity in the technical inputs data. 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.

Turning to human inputs, we find that the ratio of foreign graduate students to total graduate students (FORTGR) had a significant and positive effect in all six patenting equations. The elasticity of total patent applications to increases in foreign students is around 0.48 and between 0.60 and 0.99 for patents awarded. The impact was larger on future university patent awards than on other patenting in specifications (6) and

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[21] The equations were estimated also without the unemployment rate, with virtually no difference in results.

(7), which control for total graduate enrollment, though both elasticities are significant and large. For its part, skilled immigration (IMCUM) had a consistently positive impact on applications and grants in all specifications, with an elasticity of around 0.1.

It is of interest to put these elasticities in perspective by computing the implied impacts on patent levels from a change in enrollments or skilled immigration. Computed at sample means, a ten-percent 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 10,589. Applying the estimated elasticity of 0.48 (from regression (8) in Table 3) 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 6,636 (or around 4.7 percent of mean total applications of 141,092). Thus, we compute a marginal impact of another foreign graduate student to be around 0.63 patent applications. Turning to total patent grants (using the coefficient from regression (4) in Table 2), a ten-percent rise in the ratio FORTGR would expand later patent grants by 6,560 (or around 7.3 percent of mean total grants), suggesting a marginal productivity of 0.62 grants. These are large figures in the context of U.S. patent flows.[22]

Turning to the breakdown into university and non-university awards, consider the coefficients on FORTGR in regressions (9) and (10). Our calculations find that a ten-percent rise in the ratio of foreign graduate students would generate another 56 university grants (an increase of 5.3 percent of mean total grants of 1,068) and another 5,979 private

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[22] 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.

(non-university) patent grants (an increase of 6.7 percent).[23] 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. Thus, a ten-percent rise in the six-year cumulated number of skilled immigrants would increase later patent applications by 1,037 (0.7 percent of sample mean), university grants by 12 (1.1 percent) and other-institution grants by 814 (0.9 percent). It seems from these computations that skilled immigration has considerably smaller impacts on patenting activity than does enrollment of foreign graduate students. Finally, a ten-percent rise in the number of scientists and engineers in the labor force (SK), holding fixed the labor force, would increase later patent applications by 10,534 (7.5 percent of sample mean), university grants by 68 (6.4 percent) and other-institution grants by 5,660 (6.4 percent).

Summing up the results, it is evident that skilled immigrants, as well as PhDs in science and engineering, have a positive impact on total patent applications as well as patents awarded to universities, industries and other enterprises. This underscores the contributions made by skilled immigrants to innovation at all levels of the U.S. economy. Innovation and patenting by both universities and non-university institutions are increased as a result of the Bayh-Dole legislation of 1980.

Next, 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

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[23] 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 estimating equation (4) in Table 2.

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. Research is frequently sub-contracted by industries to universities with a share of royalties awarded to the contributing academic department. Furthermore, industries also tend to purchase the intellectual property rights of any discovery from the innovating university and hence tend to benefit indirectly from international student contributions.[24]

It is interesting that the results consistently show that foreign students, skilled immigrants, and doctorates in science and engineering play a major role in driving scientific innovation in the United States. It should be noted that our variable includes all graduate students and not just those in science and engineering. There are only a few observations available that distinguish between domestic and foreign graduate students in these technical fields. These data indicate that enrollments of domestic students as a proportion of total graduate students have remained fairly steady at around 65 percent in recent years. However, the former accounted for an average of only 45% of all graduating students during the 1990s, suggesting a significantly larger school-leaving rate. Furthermore, a significant proportion of U.S.-born students go into other fields, such as law and management, perhaps due in part to under-preparation in mathematics

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[24] Dasgupta and David (1992) and Cohen, Florida, and Goe (1994), Laursen and Salter (2004)

and science[25]. U.S. census data indicate that only nine percent of U.S.-born graduates work in scientific fields whereas 17 percent of foreign-born graduates work in scientific fields.

The results also indicate indirectly that the United States gains from trade in graduate education services. Relatively open access to international students has allowed U.S. universities to accept the brightest graduate students in science and engineering from all over the world. In turn, international graduate students contribute to innovation and patenting. Presumably, this is because international graduate students are relatively concentrated in such fields as science and engineering. Indeed, in a number of highly ranked engineering schools, international students account for nearly 80 percent of doctoral students, while in fields such as law they rank as low as one percent.[26] 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, including international faculty, exchange visitors, research fellows and post-doctoral research associates, is a significant factor behind sharp increases in innovation and patenting at universities.

5. Concluding Remarks

This study provides the first systematic econometric results about the contributions of foreign graduate students and skilled immigrants to U.S. innovation and technological change. While it may have become conventional wisdom in some circles

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[25] http://thestar.com.my/news/story.asp?file=/2004/12/7/latest/20038USstudent&sec=latest
[26] *Open Doors*, Institute for International Education

that these personnel flows contributed extensively to learning in the United States, the idea had not been tested. Our results strongly favor the view that foreign graduate students and immigrants under technical visas are significant inputs into developing new technologies in the American economy. The impacts are particularly pronounced within the universities but spill over as well to non-university patenting.

The significant contributions of international graduate students and skilled immigrants to patenting and innovations in the United States may have international and domestic policy implications. At the international level, it is evident that the United States has a significant direct comparative advantage in exporting the services of higher education, especially in training scientists, engineers, and related personnel. This situation is broadened by the contributions of foreign students to innovation in the United States, whereby the indirect impact of technical education is additional patent rents.

However, as other countries such as Singapore improve their offerings of scientific graduate education (Furman and Hayes, 2004; Koh and Wong, 2005) and encourage them to stay on after graduation,[27] visa restrictions in the United States could have adverse implications for competitiveness. Specifically, global liberalization of higher education services would permit U.S. universities to get around visa problems by locating research campuses in other countries, such as Singapore,[28] that welcome international talent (Amsden and Tschang, 2003), following the examples of INSEAD and the University of New South Wales. Indeed, studies indicate that Japanese corporations have moved research activities abroad partly in response to strict Japanese immigration policies (Iwasa and Odatiri, 2004). It is also noteworthy that U.S.

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[27] http://straitstimes.asia1.com.sg/topstories/story/0,4386,277901,00.html?
[28] "Singapore's Man With a Plan," *The Economist,* August 14, 2004.

corporations have significantly increased patenting activity and innovation abroad

(Maskus 2000) and recent evidence indicates that the U.S. universities are also

increasingly collaborating with universities abroad (Adams et al. 2004).

One of the striking implications of the current paper is that reducing foreign

students by tighter enforcement of visa restraints could reduce innovative activity

significantly. Indeed, with the rapid economic development of countries in regions such

as South East Asia and with global job mobility increasing, such restrictions are likely to

be self-defeating, at least in economic terms.

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Table 1. Correlations among Variables

	IPA	IPG	UIPG	OIPG	TGR*	FGR*	SED*	IMCUM	SK	RD	URD	ORD	TPS5*	TPS7*	UPS7*	OPS7*	BD
IPA	1.0																
IPG	0.83	1.0															
UIPG	0.87	0.63	1.0														
OIPG	0.81	0.99	0.59	1.0													
TGR*	0.05	-0.32	0.43	-0.35	1.0												
FGR*	0.79	0.69	0.76	0.67	-0.07	1.0											
SED*	0.55	0.60	0.44	0.59	0.16	0.09	1.0										
IMCUM	0.72	0.39	0.88	0.35	0.56	0.47	0.41	1.0									
SK	0.67	0.79	0.49	0.79	-0.13	0.34	0.80	0.30	1.0								
RD	0.76	0.55	0.84	0.52	0.49	0.59	0.62	0.71	0.59	1.0							
URD	0.73	0.42	0.94	0.38	0.61	0.70	0.35	0.80	0.35	0.89	1.0						
ORD	0.76	0.55	0.83	0.53	0.48	0.58	0.63	0.70	0.60	0.99	0.88	1.0					
TPS5*	0.64	0.64	0.37	0.64	-0.21	0.28	0.69	0.33	0.69	0.53	0.24	0.54	1.0				
TPS7*	0.79	0.82	0.54	0.82	-0.23	0.53	0.68	0.35	0.80	0.64	0.42	0.65	0.93	1.0			
UPS7*	0.86	0.61	0.99	0.57	0.43	0.77	0.41	0.86	0.47	0.86	0.95	0.85	0.38	0.55	1.0		
OPS7*	0.78	0.83	0.49	0.83	-0.30	0.48	0.70	0.37	0.79	0.57	0.32	0.58	0.95	0.98	0.49	1.0	
BD	0.22	-0.07	0.59	-0.11	0.72	0.39	-0.16	0.52	-0.17	0.45	0.72	0.44	-0.43	-0.26	0.60	-0.35	1.0

*TGR is total graduate students (TOTGR); FGR is foreign graduate students (FORTGR); SED is SEDDOCCUM; TPS5 (TPS7) is TOTPATSTOCK lagged 5 (7) years; UPS7 is UPATSTOCK lagged 7 years; OPS7 is OPATSTOCK lagged 7 years.

Table 2. International Students, Skilled Immigration, and Patenting Activity in the United States, 1965-2001

	IPA (1)	IPG (2)	IPA (3)	IPG (4)
CONSTANT	4.924	2.379	5.105	3.992
	(1.35)	(0.62)	(3.06)*	(2.38)**
FORTGR	0.465	0.635	0.478	0.734
	(2.03)**	(2.67)*	(7.35)*	(7.09)*
TOTGR	-0.015	-0.137		
	(-0.06)	(-0.46)		
SEDOCCUM	0.201	0.567	0.199	0.544
	(1.94)**	(4.68)*	(2.02)**	(4.90)*
IMCUM	0.074	0.098	0.074	0.091
	(2.29)**	(2.48)**	(2.33)**	(2.45)**
SK	0.750	0.925	0.758	0.979
	(2.57)*	(2.89)*	(2.99)*	(3.36)*
RD	-0.177	0.320	-0.181	0.049
	(-1.04)	(1.62)***	(-1.19)	(0.20)
TOTPATSTOCK	0.533	0.084	0.536	0.273
	(3.60)*	(0.35)	(3.99)*	(1.61)***
BD	0.140	0.272	0.142	0.283
	(2.36)**	(4.42)*	(2.65)*	(4.93)*
TIME	-0.006	-0.025	-0.006	-0.028
	(-0.69)	(-2.67)**	(-1.25)	(-4.71)*
UNEMPLOY	0.007	0.048	0.007	0.053
	(0.14)	(0.94)	(0.15)	(1.05)
R-Squared	0.94	0.94	0.94	0.94
DW	1.61	2.54	1.61	2.56

Notes: IPA is patent applications and IPG is patents granted, both as a percentage of labor force. FORTGR is foreign graduate students as a proportion of total graduate students. TOTGR is total graduate students as a proportion of labor force. SEDDOCCUM is the cumulative number of doctorates earned in engineering and science in U.S. universities over a period of five years as a percentage of labor force. IMCUM 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 labor force. RD is total real R&D expenditures as a proportion of labor force. TOTPATSTOCK is cumulative patents awarded as a proportion of labor force. BD is the dummy variable for the Bayh-Dole Act. Variables in the IPA equations are lagged five years, while those in the IPG equations are lagged seven years. Figures in parentheses are t-ratios and marked as significantly different from zero at the one-percent (*), five-percent (**) and ten-percent (***) levels.

Table 3. International Students, Skilled Immigration, and Patenting Activity in the United States, 1965-2001

	IPA (5)	UIPG (6)	OIPG (7)	IPA (8)	UIPG (9)	OIPG (10)
CONSTANT	5.099 (1.43)	8.136 (1.82)**	2.038 (0.56)	5.068 (3.09)*	2.705 (1.29)	3.589 (2.31)**
FORTGR	0.469 (2.06)**	0.986 (3.00)*	0.616 (2.64)*	0.480 (7.46)*	0.604 (3.64)*	0.676 (5.95)*
TOTGR	-0.009 (-0.04)	0.535 (1.36)	-0.104 (-0.36)			
SEDDOCCUM	0.200 (1.94)**	0.383 (2.37)**	0.586 (4.99)*	0.200 (2.03)**	0.445 (2.82)*	0.564 (5.09)*
IMCUM	0.073 (2.29)**	0.119 (2.62)*	0.103 (2.84)*	0.075 (2.40)**	0.128 (2.78)*	0.092 (2.63)*
SK	0.760 (2.62)*	0.928 (2.08)**	0.903 (2.92)*	0.762 (3.00)*	0.732 (1.71)***	0.940 (3.25)*
RD	-0.191 (-1.17)			-0.177 (-1.19)		
URD		0.002 (0.01)			0.021 (0.10)	
ORD			0.470 (2.84)*			0.383 (2.46)**
TOTPATSTOCK	0.530 (3.65)*			0.526 (3.96)*		
UPATSTOCK		0.570 (2.28)**	0.192 (1.69)***		0.439 (1.83)***	0.183 (1.10)
OPATSTOCK		0.159 (0.41)	0.244 (1.48)		0.211 (0.56)	-0.158 (-0.51)
BD	0.137 (2.31)**	0.322 (3.43)*	0.253 (3.99)*	0.140 (2.55)**	0.288 (3.13)*	0.257 (4.22)*
TIME	-0.006 (-0.65)	-0.009 (-0.33)	-0.039 (-2.55)**	-0.007 (-1.29)	0.014 (0.57)	-0.040 (-3.67)*
UNEMPLOY	0.004 (0.08)	0.155 (1.18)	0.036 (0.69)	0.006 (0.13)	0.141 (1.60)	0.037 (0.72)
R-Squared	0.94	0.99	0.94	0.94	0.99	0.94
DW	1.60	1.90	2.50	1.60	1.82	2.52

Notes: IPA is patent applications and IPG is patents granted, both as a percentage of labor force. FORTGR is foreign graduate students as a proportion of total graduate students. TOTGR is total graduate students as a proportion of labor force. SEDDOCCUM is the cumulative number of doctorates earned in engineering and science in U.S. universities over a period of five years as a percentage of labor force. IMCUM 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 labor force. RD is total real R&D expenditures as a proportion of labor force. TOTPATSTOCK is cumulative patents awarded as a proportion of labor force. BD is the dummy variable for the Bayh-Dole Act. Variables in the IPA equations are lagged five years, while those in the IPG equations are lagged seven years. Figures in parentheses are t-ratios and marked as significantly different from zero at the one-percent (*), five-percent (**) and ten-percent (***) levels.