# Visa Screening and Collateral Import of Terrorism*

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**Abstract**

The paper addresses the issue of imperfect visa scrutiny by the government and the sponsoring of foreign scholars by institutions offering higher education. A static game-theoretic model between the higher-education sector and the government is postulated. In the presence of delay costs, both the numbers of foreign scholars sponsored and the intensity of visa screening are higher than their efficient levels. As the proportion of bad applicants (who are potential terrorists) for visa increases, the number of foreign scholars sponsored may increase or decrease, but the number of bad applicants who succeed in obtaining visa may very well decrease, lowering the security risk.

**JEL Classification:** C72, D74
**Keywords:** Terrorism, visa, information asymmetry

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# 1 Introduction

*9/11* has led to an overhaul of the U.S. immigration system. Because some of the hijackers had entered the country through student visa, these visa applications are now subject to elaborate and time consuming terrorism-related background checks.[1]

There is an obvious benefit from security checks, as they reduce the inflow of potential terrorists into the homeland of the U.S. On the other hand, because of errors and delays involved in the visa-issuing process, colleges and universities in the U.S. potentially lose out outstanding foreign scholars in terms of their contribution to the knowledge base in the U.S. Since foreign students constitute a major fraction of total students in graduate programs in the U.S., the post-*9/11* visa regime is a matter of great concern for the 'higher-education sector'.[2] There is obviously a tension between the interest and the mission of the higher-education institutions on one hand and that of the Department of Homeland security on the other – although both may be appreciative of each other's concern in principle.

The objective of this paper is to build a simple game-theoretic model of the behavior of the higher-education sector (briefly, the 'education sector') and the Department of Homeland Security (the 'Department', for short) with regard to the important issues of sponsoring scholars/students from abroad, choosing the intensity of individual background checks etc. Our underlying critical assumption is that screening is imperfect at best: there is always a positive probability that some potential terrorists are not detected by the system and hence are able to enter the country. We study how the equilibrium level of screening intensity and the number foreign scholars sponsored

[1] Prior to *9/11*, the State Department would transmit an applicant's background information to agencies like CIA and FBI, and if no response was obtained within a stipulated time, a visa will be issued (if other things are in order). Now, in addition to 'standard' background checks, a consulate must obtain a positive response from these agencies before it can issue a visa. There is also TAL (Technology Alert List) check or 'Visa Mantis Review', introduced in 2000, and Visa Condor program initiated in 2002. Whereas the purpose of the former is to prevent the export of sensitive information through graduate-level study, the latter is meant to catch would-be terrorists.

[2] According to the U.S. Department of Education (2002), 38.2% of doctorates in physical sciences were received by non-resident 'aliens' and the corresponding figure in social sciences was 22.8%. The high proportion of international students in the graduate programs get reflected in the large number of successful scientists born abroad and working in the U.S. According to Tilghman (2003), 20% of the members of the National Academy of Sciences are of foreign origin. About one-third of Nobel laureates from the U.S. are foreign-born.

deviate from their 'efficient' levels. We also examine the effect of 'an increase in terrorism abroad'.

*Ceteris paribus*, imperfect screening imposes two types of costs on the education sector. It is possible that some 'good' applicants are wrongly associated with terrorism and denied visa – which is especially relevant for applicants from countries that U.S. believes to be particularly associated with terrorism. We call this the case of *mistaken identity*. Alternatively, it can be argued that good applicants face zero probability of being linked to terrorism, while some bad applicants pass the scrutiny because of the imperfection in screening. However, due to delays in processing visa applications, some good scholars miss relevant deadlines and are unable to enter the country and possibly go somewhere else like Europe, Canada and Australia. We call it the case of *delay*.[3] These two cases are considered in turn in the following two sections.

# 2 Mistaken Identity

The supply of student/scholar visa applicants is infinitely elastic. Of these, there are two types of visa applicants: (i) 'bad' applicants (potential or would-be terrorists) and (ii) 'good' applicants (genuine scholars). There is asymmetric information: each applicant knows his/her type, while the Department doesn't. It is thus an adverse selection problem. Let $c$ be the cost per applicant for conducting background checks. Let $p_g(c)$ and $p_b(c)$ be respectively the probabilities of correctly assessing a good and a bad applicant's true type. There is a monotone mapping from $c$ to $p_i \in (0, 1)$, with $p_i'(c) > 0 > p_i''(c),\ (i = b, g)$, where the Department chooses $c$. We shall refer to an increase in $c$ synonymously as an increase in the intensity of visa screening. There is a common knowledge that an exogenous proportion, $q$, of the pool of applicants is bad. An increase in $q$ reflects a rise in terrorism threat.

[3] In recent months the U.S. administration has acknowledged the problem and is trying to "achieve a faster and more secure ... process of welcoming foreign visitors to the US." (*Financial Times*, 18 January, 2006). According to the *Chronicle of Higher Education* (October 28,2004) the U.S. State Department acknowledges that fostering academic and scientific exchanges is crucial to the national security of the United States and is trying to balance, 'secure borders' and 'open doors.' This move comes, according to the *Financial Times*, "amid mounting concerns in the Bush administration ..that talented students ... are going to other countries ..."

Let $V$ denote the total number of foreign scholars, sponsored by the education sector and issued visa initiating documents (such as I-20, invitation letters, job offers etc.). Assuming the law of large numbers, among the bad applicants (whose number is $Vq$), $Vqp_b$ persons are denied visa. Security problems arise from bad applicants able to pass screening and their number equals $T \equiv Vq(1-p_b)$; this is the collateral import of terrorism. Among the good applicants, $V(1-q)p_g$ obtain visa, while $V(1-q)(1-p_g)$ do not. The latter imposes an indirect cost on the education sector.

Consider a simultaneous game between the education sector and the Department.

## 2.1 Behavior of the Education Sector

Because of the assumption of infinite supply of potential applicants, there is no strategic interaction between institutions in the education sector. Hence, for simplicity, we can consider the education sector as one entity.[4]

There are benefits of this sector from sponsoring foreign scholars, and, these are a function of the number of good applicants who are able to get visa. The benefits include the value of the knowledge base offered by the good scholars who able to enter the country. Let these be indicated by the function $B[V(1-q)p_g]$, $B' > 0 > B''$.[5] For simplicity, we shall assume this function takes the form $B(\cdot) = \ln(\cdot)$, which is akin to the log-linear utility function used in many macro models.[6]

As for direct costs, there are two types. First, there are costs per foreign scholars who turn up, and these include financial aid packages, costs of supporting their conference participation, teaching, collaborative research, providing infrastructure etc. These costs are $nV(1-q)p_g$, where $n$ is such cost per head. Second, there are costs per student/scholar sponsored, denoted by $m$, and

[4]Of course, there is, sometimes, competition among institutions to attract the very best from abroad. However, the emphasis of our analysis lies elsewhere, namely, in the tension between the education sector and the security concern of the country.

[5]There is no benefit from bad successful applicants who manage to get visa. They are assumed to abscond as soon as they arrive in the country.

[6]The marginal benefit from sponsoring foreign scholars is equal to $B'(\cdot)(1-q)p_g$. An increase in $p_g$ affects the marginal benefit in two ways. First, it is like a technical progress, enhancing the marginal benefit from $V$. Second, because of diminishing marginal benefit it tends to reduce the marginal benefit from $V$. By assuming this particular function form of $B(\cdot)$ we take the net impact of these two effects to be negligible.

these include the direct cost of issuing a visa initiating document as well as costs associated with recruitment process; such costs are equal to $mV$.

We assume that the education sector seeks to maximize the difference between these benefits and the costs, i.e., maximize $\Pi(V, c; \cdot) = \ln[V(1-q)p_g(c)] - mV - nV(1-q)p_g(c)$ by choosing $V$. This immediately raises the question as to whether this sector cares about the threat of terrorism from admitting bad applicants. Our position is that it does, like other individuals or institutions in the society, but it is simply do not have the resources or expertise to make a good judgment on who may, or who may not, be a potential terrorist. As a matter of practice, compared to domestic students, the application forms for foreign students are more particular about how they would manage to finance their education rather than anything else. Given the objective function postulated above, the first-order condition is:[7]

$$\Pi_V = \frac{1}{V} - m - n(1-q)p_g(c) = 0. \tag{1}$$

An important feature of the current model is that an increase in the intensity of visa screening *increases* the number of good applicants being able to obtain visa and therefore benefits the education sector. Hence it is induced to reduce $V$. That is, (1) gives a negatively sloped best-response function between $c$ and $V$, shown as the $E_1E_1$ curve in Figure 1.

## 2.2 Behavior of the Department

The Department is assumed to minimize the sum of potential damage from terror stemming from the entry of bad applicants and the total cost of running security checks on all visa applicants. The former is expressed through the function $F(T)$, with $F' > 0$ and $F'' > 0$. Since mass fear which is highly contagious, is one of the most distinguishing features of terrorism *vis-á-vis* individual crime or guerrilla war, this function should be broadly interpreted as inclusive of psychological damage caused in terms of fear and insecurity among the common people (Becker and Rubinstein, 2004),

[7] It is easily verified that the second-order condition is met.

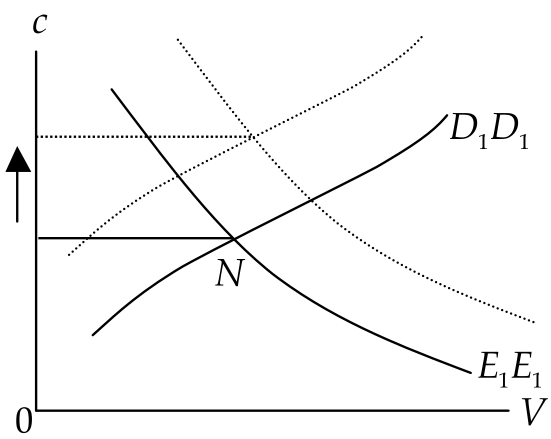


Figure 1: Nash Equilibrium

and not just the material damage in the form of death, injury and destruction of property. This broad interpretation motivates that $F''(\cdot) > 0$. Furthermore, it is to be noted that $F(\cdot)$ denotes the perceived or potential threat to security, not necessarily the actual damage done. Also, it embodies the role of internal security measures, assumed to be exogenous.[8]

We write the objective function of the Department as $\max_c \Omega(V, c; \cdot) = -F[Vq(1-p_b(c))] - Vc$. The first-order condition is:[9]

$$\frac{\Omega_c}{V} = qp_b'(c)F'(T) - 1 = 0. \tag{2}$$

Eq. (2) gives a positively sloped best response function, shown by the $D_1D_1$ curve in Figure 1.

The intersection of $D_1D_1$ and $E_1E_1$ (point $N$) defines the non-cooperative Nash equilibrium. We focus on the effect of an increase in $q$, the threat parameter.

As $q$ increases, the $D_1D_1$ curve and the $E_1E_1$ curve shift respectively to the left and right. Thus $c$ increases, while the effect on $V$ is ambiguous. It is easy to see that an increase in $q$ forces the Department to increase the intensity of visa screening. However, as $q$ rises, at given $c$, the number of good applicants able to get visa falls. The education sector tends to compensate this by

[8]We do not endogenize internal security measures, including for example the SEVIS system in which most colleges and universities participate.

[9]The second-order condition is satisfied.

increasing $V$. But, on the other hand, an increase in $c$ reduces the probability of mistaken identity (good mistaken as bad), thus tends to increase the number of good applicants succeeding in getting visa and thereby induces the education sector to reduce $V$. Hence the net effect on $V$ is ambiguous.

Turning to the effect on the number of bad applicants able to obtain visa, $T$ naturally increases with $q$, at given $V$ and $c$. However, the increase in $c$ tends to reduce $T$ and the ambiguous effect on $V$ implies an ambiguous effect on $T$. Thus, there remains the possibility of a 'paradoxical' outcome – i.e. $T$ falls. In fact, it follows from (2) that $T$ does indeed fall when $p_b''$ is not large, i.e., $dT/dq < 0$ if $p_b'' \simeq 0$.[10]

Intuitively, if $p_b'$ is constant, the marginal benefit from screening (in terms of reducing security risk) monotonically increases with $q$ and $T$. Hence, as $q$ increases, the marginal benefit exceeds the (given) marginal cost. The latter remaining unchanged, it implies that visa screening must increase to the extent such that $T$ falls and the marginal benefit falls back to its original level.

**Proposition 1** *As the proportion of bad visa applicants increases, (a) visa scrutiny becomes more intense, (b) the number of foreign scholars sponsored by the education sector may increase or decrease and (c) the number of bad applicants able to obtain visa may increase or decrease in general, but decreases unambiguously if $p_b'' \simeq 0$.*

Part (c) is particularly noteworthy and is like a "fortress effect" in the sense that an increase in threat from outside may trigger security enhancements to the extent that the territory is less vulnerable than before.[11]

[10] In this case, $qF'(T)$ must remain unchanged. Hence an increase in $q$ must imply a decline in $F'(T)$. Given $F'' > 0$, it implies a decline in $T$.

[11] As a seminar participant has pointed out, this is similar to a threat to health by, say a mild heart attack, which can actually make a person healthier than before, as she/he is induced to maintain a regimen of exercise and diet.

### 2.3 The First Best

We now characterize the first best, which takes into consideration the interests of both parties with equal weight. Think of a social planner who maximizes $\Pi(V, c; \cdot) + \Omega(c, V; \cdot) \equiv W(V, c; \cdot)$. We call the outcome the efficient solution. This is characterized by the first-order conditions:[12]

$$W_V = \Pi_V + \Omega_V = \frac{1}{V} - m - n(1-q)p_g - q(1-p_b)F'(T) - c = 0 \tag{3}$$

$$W_c = \Pi_c + \Omega_c = \frac{p_g'(c)}{p_g(c)} - nV(1-q)p_g'(c) + VqF'(T)p_b'(c) - V = 0. \tag{4}$$

The following proposition compares the non-cooperative equilibrium with the efficient outcome.

**Proposition 2** *Relative to the efficient solution, in the non-cooperative equilibrium more foreign scholars are sponsored, whereas visa scrutiny may be more or less intense.*

While this is proved in Appendix 1, intuitively, at the non-cooperative equilibrium the education sector is not concerned with terrorist threat *per se.* At given $c$ an increase in the number of scholars sponsored raises the damage from potential terrorism as well as total screening costs. Hence the number of sponsorships in the first best solution that includes the interests of the Department is less – which is same as saying that there are more sponsorships under non-cooperation than what is ideal. A smaller number of sponsorships under first best implies a lower marginal benefit from security screening and thus less screening. But, on the other hand, an increase in security screening benefits the education sector (in terms of a smaller probability of mistaken identity); this implies more intense screening under first best. Hence the comparison relating to $c$ is ambiguous.

Also as shown in Appendix 1, the number of bad applicants who are able to enter is less under first best than under non-cooperation. That is, under non-cooperation, the national security risk is more. Intuitively, if we consider a move from non-cooperation to first best, a decrease in $V$ tends to lower $T$. But because of the conflicting effects on $c$, the magnitude of the effect through the

[12]In Appendix 1 it is proved that the second-order conditions are met.

change in $c$, if at all positive on $T$, is less than that of $V$. Hence, the effect of $V$ on $T$ dominates. Therefore,

**Proposition 3** *Relative to the non-cooperative solution, under the first best, the expected number of bad applicants being granted visa is smaller.*

## 3 Delay

Educational institutions have especially voiced their concern about the delay that current visa screening procedures cause to prospective visa applicants.[13] Delay can be caused by a number of factors. Of course, the focus here is on the delay-effect due to screening. *Ceteris paribus*, an increase in the intensity of background checks represented by the cost variable $c$ makes visa processing longer. Specifically, suppose there is an interval of time $(0, H)$, where $H$ is the deadline to enter the country. (In this one-shot model, there is no entry after that date.) Visa applications are received over the entire range from 0 to $H$ following an uniform distribution.[14] That is, $1/H$ proportion of $V$ per day or $V/H$ visa applications per day arrive at the consulate. If $M$ denotes the number of employees handling visa, one employee handles $V/(MH)$ applications daily. The time taken to go through all the background security checks of an application presumably increases with both $V/(MH)$ and $c$, and, let this be captured by the function $\tau = \tilde{\tau}[V/(MH), c]$. However, in order to emphasize the delay due to security checks, assume that the ratio of $V/M$ is constant, i.e., as the number of visa applications increases, the Department hires proportionately more employees. Thus the work load of an employee varies directly with $c$. Without loss of generality, normalize both $H$ and $V/M$ to 1. Then we can write $\tau = \tilde{\tau}(1, c) \equiv \tilde{\tau}(c)$.

It follows that those who apply between 0 to $(1 - \tau)$ get their visa processed in time and let

[13] According to the *Financial Times* (14 November 2005), the number of international students enrolled at US universities dropped for the second consecutive year, and as a result leading figures from the US education sector have been calling for improvements to student visa policy. They fear that that falling numbers of international students could hurt US competitiveness.

[14] There are various reasons as to why visa applications would reach a consulate on different dates, even if the deadline is the same.

$\mathcal{V} \equiv V[1-\tau(c)]$ be the number of such visa applications.[15] Define $\mu(c) \equiv 1-\tau(c)$. Then $\mathcal{V} = V\mu(c)$, where $\mu(c) \in [0,1]$ and $\mu'(c) < 0$. It is reasonable to suppose $\mu(0) = 1$ and $\mu(\infty) = 0$. Moreover, let $\mu'' \geq 0$, meaning a non-increasing marginal impact of screening on delay.[16]

We further assume that all 'good' applicants that apply for visa in time get the entry permit i.e., there is no cost of mistaken identity. But, as before, there is always a chance that the bad may pass as good. The proportion of such applicants (among the bad) is $1 - p_b(c)$.[17] Thus, the number of 'good' and 'bad' applicants who obtain visa are respectively: $S = (1-q)V\mu(c)$ and $T = qV[1 - p_b(c)]\mu(c)$.

The objective function of the education sector is now $\Pi(\cdot) = \ln S - mV - nS$. In the non-cooperative environment it is maximized with respect to $V$ yielding the first-order condition:

$$\Pi_V = \frac{1}{V} - m - n(1-q)\mu(c) = 0. \tag{5}$$

The critical difference with the earlier model is that, (5) implies a positive best response function, depicted by the $E_2E_2$ curve in Figure 2. It is because, as $c$ increases, the number of good applicants able to obtain visa in time falls and the education sector responds by sponsoring more foreign scholars.

The Department maximizes $\Omega(c, V) = -F(T) - Vc$ and the first-order condition is:[18]

$$\frac{\Omega_c}{V} = qF'(\cdot)[\mu(c)p_b'(c) - (1 - p_b(c))\mu'(c)] - 1 = 0. \tag{6}$$

Compared to the previous model, note that there is an additional benefit from screening – namely, by causing delay, it acts as a further entry deterrence for bad applicants. Eq. (6) leads to the

[15]In this section we assume that $c$ includes the cost of hiring employees to handle one applicant.

[16]It may be argued that the bad applicants will take extra care to always apply early enough. This is indeed simpler to analyze since the security-benefit from screening is exactly same as in the previous model. All our results go through.

[17]We imagine the following screening scenario. There is a checklist which every applicant has to satisfy. Good applicants have 'nothing to hide' and thus all of them satisfy the checklist. But, only a fraction $(1 - p_b(c))$ of the 'bad' applicants manage to achieve the same.

[18]We have $\Omega_{cc}/V = qF'[2\mu' p_b' + \mu p_b'' - (1-p_b)\mu''] - Vq^2F''[\mu p_b' - (1-p_b)\mu']^2$, implying that the second-order condition is met.

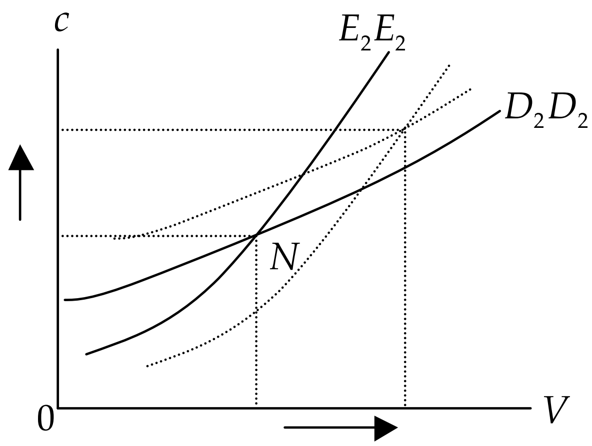


Figure 2: Nash Equilibrium in the Presence of Delay

upward-sloping best response function $D_2D_2$. It is straightforward to prove that $E_2E_2$ is steeper than $D_2D_2$.[19]

We are now ready for comparative statics. From (5) and (6) respectively, as $q$ increases, the $E_2E_2$ curve shifts to the right and the $D_2D_2$ curve to the left. The effects on $V$ and $c$ are clear-cut: both increase unambiguously. The reason for an increase in $c$ is obvious and same as in the previous case. But, unlike in the mistaken-identity case, an increase in $c$ adversely affects the education sector. Thus the adjustments in both $q$ and $c$ impose a higher cost to the education sector and it responds by increasing $V$.

Turning to the effect on $T$, as in the previous model, $dT/dq \gtrless 0$. However, the possibility of $dT/dq < 0$ is somewhat weaker than in the previous model – because while the marginal security benefit from screening increases with $q$ and $T$, it falls with the level of screening, which increases with $q$.

**Proposition 4** *In the presence of delay, at the non-cooperative equilibrium, as the proportion of bad*

[19]Let $\Delta \equiv \Omega_{cc}\Pi_{VV} - \Omega_{cV}\Pi_{Vc}$. Using (5), it can be shown that

$$\Delta = -\frac{qF'[2\mu' p_b' + mp_b'' - (1-p_b)\mu'']}{V} + q^2F''[\mu p_b - (1-p_b)\mu'][\mu p_b - Vm(1-p_b)\mu'] > 0,$$

which implies that the $E_2E_2$ curve is steeper.

*visa applicants increases, the screening intensity as well as the number of foreign scholars sponsored increase. The number of bad applicants being able to obtain visa may increase or decrease.*

Lastly we characterize the first best in the presence of delay effects. Given that the planner maximizes $L \equiv \Pi(V, c) + \Omega(c, V)$ with respect to $V$ and $c$, the first-order conditions are:

$$L_V = \Pi_V + \Omega_V = \frac{1}{V} - m - n(1-q)\mu(c) - q\mu(c)(1-p_b)F'(T) - c = 0, \tag{7}$$

$$\frac{L_c}{V} = \frac{\Pi_c + \Omega_c}{V} = \frac{\mu'(c)}{\mu(c)} \cdot \left[\frac{1}{V} - n(1-q)\mu(c)\right] + qF'(\cdot)[\mu(c)p_b'(c) - (1-p_b(c))\mu'(c)] - 1 = 0. \tag{8}$$

Comparing this solution with the non-cooperative one, we get a stronger result than Proposition 2. In Appendix 2 it is proved that

**Proposition 5** *Both the number of scholars sponsored for visa and the intensity of screening are higher than their efficient levels.*

The reason why the number of scholars sponsored is greater is the same as in the previous model, namely, the adverse effect of an increase in the number of sponsorships on the interests of the Department which is not internalized at the non-cooperative equilibrium. Also, as in the previous model a higher $V$ implies a higher $p$. But, unlike in the previous model an increase in $p$ *adversely* affects the education sector, and, the lack of internalization of this effect implies a higher $p$ too. Hence, in the non-cooperative equilibrium $p$ is unambiguously higher than its efficient level.

The comparison of the expected number of bad applicants getting visa is different however. Because both $V$ and $p$ under non-cooperation are higher than their efficient levels, and $V$ and $p$ affect $T$ in opposite directions, there is a possibility that the first-best may imply accepting a higher security risk. Such a possibility should not however be seen as "unacceptable." *Ceteris paribus*, national security is a matter of degree and has its price; when this is taken into consideration, it cannot be ruled out that a marginal increase in security risk is associated with a higher aggregate welfare.[20]

## 4 Conclusions

By developing a simple game-theoretic model, this paper has analyzed the issue of sponsorship of foreign scholars and visa scrutiny in the presence of a threat of terrorism. Considering the interests of the 'university sector' and the Department of Homeland Security, our analysis yields, *inter alia*, that (i) in the non-cooperative equilibrium too many foreign scholars are sponsored, (ii) if delay in issuing visas is a significant factor, visa screening is too severe, compared to what is ideal, and (iii) a rise in terrorism sentiments abroad does not necessarily translate into a higher security threat in equilibrium. It is a fact that in the post-9/11 era U.S. visa screening has intensified and U.S. universities are recruiting more aggressively (*Financial Times*, November 14, 2005). Our results (i) and (ii) indicate that the levels of these responses may be over-reactions. As for result (iii), it is a reflection of the fact that an increase in (any kind of) threat can trigger a defense mechanism that may imply less vulnerability than before.

The obvious question then is: should the US government impose a quota on the total number of students to be sponsored by all universities (as it does for work visa now)? Apart from the fact that a single-number-based quota would entail various kinds of arbitrariness, the consequences of which are highly undesirable, our analysis implies that the problem is not just associated with the university sector (in terms of sponsoring too many scholars), but also with the Department of Homeland Security whose visa-screening procedures are driving many bright international students to other countries. According to an Associated Press release on 8 April 2006, the former Secretary of State Colin Powell has admitted that "The United States made visa requirements too strict" following 9/11 and as a result "many of the world's brightest international students enrolled at

[20]As said earlier, our simple model treats internal security measures as exogenous. One would conjecture that the scope of a positive association between security risk and aggregate welfare is less if these measures are optimally chosen.

universities in Canada, Europe and Asia ..." In the light of our results, what is called for is some relaxation of requirements or procedures for visa consideration and approval, especially those causing delay (accompanied by a greater stress on internal security measures), coupled with a conscious effort by the university sector to exercise some restraint in admitting/inviting foreign scholars. One way would be to raise the academic bar for outside scholars.

We must emphasize however that at this stage these policy conclusions are suggestive at best. More formal scrutiny of the issue is warranted to include, for example, an explicit consideration of internal security measures by the Department of Homeland Security and participation of the University sector itself in programs such as SEVIS.

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## Appendix 1: Mistaken Identity

### Second-Order-Conditions Check Under Cooperation

¿From the first-order conditions (3) and (4), we have

$$W_{VV} = -\frac{1}{V^2} - q^2(1-p_b)^2F'' < 0, \tag{A1}$$

$$\begin{aligned} W_{cc} &= -\left(\frac{p_g'}{p_g}\right)^2 - V^2q^2(p_b')^2F'' + VqF'p_b'' + \frac{p_g''[1-nV(1-q)p_g]}{p_g} \\ &= -\left(\frac{p_g'}{p_g}\right)^2 - V^2q^2(p_b')^2F'' + VqF'p_b'' + \frac{Vp_g''[m+q(1-p_b)F'+c]}{p_g} < 0, \text{ by using (3)} \end{aligned} \tag{A2}$$

$$\begin{aligned} W_{cV} &= -n(1-q)p_g' + qF'p_b' + Vq^2(1-p_b)p_b'F'' - 1 \\ &= Vq^2(1-p_b)p_b'F'' - \frac{p_g'}{Vp_g} \text{ by using (4)} \end{aligned} \tag{A3}$$

$$\begin{aligned} D \equiv W_{VV}W_{cc} - W_{cV}^2 = &-\left[\frac{1}{V^2} + q^2F''(1-p_b)^2\right]\left\{VqF'p_b'' + \frac{Vp_g''[m+q(1-p_b)F'+c]}{p_g}\right\} \\ &+ q^2F''\left\{(p_b')^2 + \left(\frac{p_g'}{p_g}\right)^2(1-p_b)^2 + 2V\frac{p_g'}{p_g}(1-p_b)p_b'\right\} > 0. \end{aligned}$$

The second-order conditions are met as $W_{VV} < 0$, $W_{cc} < 0$ and $D > 0$.

### Propositions 2 and 3

Proposition 2 is proved by using Figure 3. The non-cooperative equilibrium is shown at point $N$. Various regions around it indicate the signs of the partials, $\Pi_V$ and $\Omega_c$. Since $\Omega_V = -q(1-p_b)F'(T) - c < 0$, from the first-order condition (3), under efficiency, $\Pi_V > 0$. This implies $nV(1-q)p_g < 1$. Thus $\Pi_c = (p_g'/p_g)[1-nV(1-q)p_g] > 0$. In view of (4), this implies $\Omega_c < 0$. In Figure 3 we notice that $\Pi_V > 0$ and $\Omega_c < 0$ in region B, i.e. the co-operative equilibrium lies in this region. Comparing this with point $N$ proves Proposition 2.

Proposition 3 can also be proved proved with the help of Figure 3. Write (1) as $q(1-p_g(c))/T - m - n(1-q)p_g(c) = 0$, defining a negative locus between $T$ and $c$, analogous to the $E_1E_1$ curve in Figure 3. Eq. (2) implies a positive locus between $T$ and $c$, similar to $D_1D_1$. The sign structure of the partials, $\Pi_V$ and $\Omega_c$, is analogous to that in Figure 3. Since under cooperation $\Pi_V > 0$ and $\Omega_c < 0$, the efficient solution must lie in region B in the ($T$, $c$) space. This proves Proposition 3.

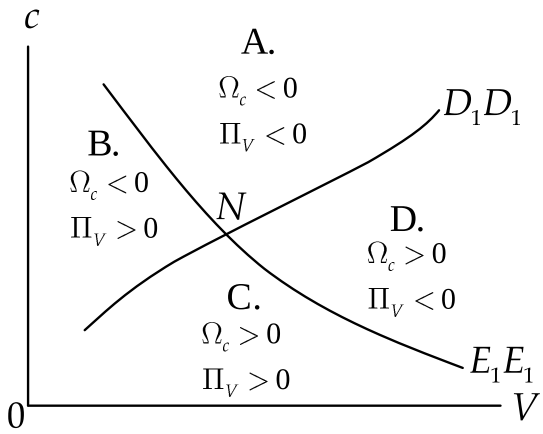


Figure 3: Comparing $V$ and $c$ between Non-Cooperative Equilibrium and Efficiency

## Appendix 2: Delay

### Proposition 5

We have $\Omega_V = -F'q\mu(c)(1-p_b)- < 0$ and this implies $\Pi_V > 0$. Now $\Pi_c = [V\mu'(c)/\mu(c)](\Pi_V + m) < 0$, and thus $\Omega_c > 0$. Hence, under efficiency, both $\Pi_V$ and $\Omega_c$ are positive. It is easy to check that in Figure 2, $\Pi_V > 0$ and $\Omega_c > 0$ in region to the South-West of the point $N$ (in between the two reaction functions). Comparing this region with point $N$ implies Proposition 5.