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Interdependent Security: The Case of Identical Agents

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1. Introduction

Security is topical. Many individuals and organizations are considering whether to invest more in security precautions. In this paper we investigate the economic incentives for such investment. Do individuals and firms have incentives to carry our socially appropriate levels of security investment? We argue that in situations where the security levels of members of a group are interdependent, incentives may be perverse: the dependence of one agent's security on the behavior of others may completely negate the payoffs he receives from investing in security. We shall refer to these cross-effects between one agent's incentives and the behavior of the others as "contamination", for reasons that will become clear later on.

We shall illustrate our general argument by reference to two specific scenarios, both of which relate to the question whether or not it is cost-effective to invest in a protective measure where there is the possibility of contamination from others who have not adopted this measure:

Scenario 1: **Be Careful** (BC) **Airlines** is considering whether to install a baggage checking system voluntarily for added protection. In making this decision it needs to balance the cost of installing and operating such a system with the reduction in the risk of an explosion from a piece of luggage not only from the passengers who check in with BC but from the checked bags from passengers who check in on other airlines and then transfer to BC.

Scenario 2: The Green family in Apartment 1 in a multi-unit building is considering investing in fire prevention equipment such as sprinkler systems to reduce the potential losses from this risk. It will incur the cost of the system if the premium reduction it receives on its insurance policy justifies the investment. This premium reduction depends on the chances of a fire to Apartment 1, which may originate in Apartment 1 or in other units in the building, some of which may not have sprinklers.

In these two scenarios, each airline or housing unit has an opportunity to protect itself by incurring a cost that reduces either the chances of it suffering a loss or the magnitude of its loss, or both. However, this reduction in risk is dependent on what protective actions are taken by other agents who can affect this risk. As we will show below the incentive to invest in protection can be greatly diminished if many other agents fail to adopt protective measures. In fact, in the limit there is **no** incentive to protect oneself due to these externalities. The decision by all agents to remain unprotected is a Nash equilibrium even though from both the vantage point of each individual unit and society there are net benefits for everyone from investing in protection.

To our knowledge this problem of interdependent security has not been examined in the literature. Orszag and Stiglitz (2002) develop a model for the optimal size of a fire department and point out that homeowners fail to take into account the positive externalities associated with reducing damage to their neighbors by building safer homes. They also note that an increase in government investment in security will tend to reduce individual investment. What they do not show is that the economic incentives for investing in preventive measures decrease as the number of unprotected homes increase. There thus is a need for either public sector intervention or coordinating mechanisms to induce this activity and reduce the need for larger fire departments.

A key question that the present paper addresses is how to induce tipping mechanisms as characterized by Schelling (1968) so that enough agents will want to invest in security that the others will choose to follow. At some level this aspect of the problem is similar to the phenomena that arise with network externalities, where a community will standardize on one of several competing products after enough members have adopted this.
(Arthur, 1994; Heal 1999).

The next section of the paper develops a model of interdependent security to illustrate the nature of the externalities that creates a disincentive to invest in protection. Section 3 discusses the implications of the solution and how one can internalize these externalities using coordinating mechanisms and/or intervention by the public sector. In Section 4 we examine other forms of protection, such as burglar alarms to deter theft and vaccines to prevent disease, to see in what ways these actions differ from the model characterizing fire prevention or baggage security. The concluding section discusses future research.

2. A Model of Interdependent Security

We consider a 1 period model where there are n risk-neutral agents designated as A_i $i=1...n$. These are the primary actors, who have to choose whether or not to invest in security. In the fire prevention scenario described above, these are apartment owners who choose whether or not to install sprinklers. In the airline scenario, these are airlines choosing whether or not to invest enough to do a thorough job of screening baggage that is being checked.

Each agent faces a risk of damage; if the damage materializes then the loss is L. There are two possible ways in which damage can occur: it can start on the agent's own property or on the property of another agent. The probability of damage arising from an event on the agent's own property if he has not invested in security precautions is p, so that the expected loss from this event is pL. If he has invested in security precautions then this risk is zero. The situation is completely symmetric and all agents are identical.

As we noted, damage may arise on an agent's own property or on the property of another. In terms of the earlier scenarios, a fire in a neighboring house may cause my house to catch fire. A sprinkler system in my house will ensure that it is not destroyed by a fire arising internally, but will not protect it against fires arising outside. And for the airline scenario, thorough scanning of baggage that BC has checked itself will prevent damage from these bags, but there could still be an explosive in an unchecked bag transferred from another airline to BC.

There is therefore an additional risk of loss due to "contagion" from other agents who have not invested in loss prevention. If there are only two agents, this contagion risk to agent 1 is the probability that agent 2 suffers damage, p, times the probability that damage occurring at agent 2 causes damage to agent 1, which we denote by q. We focus first on the case of two agents, as this presents the basic intuitions in a simple framework, and then turn to the multi-agent case

The 2- Agent Problem

Assume that each agent has two choices: to invest in security, S or not to do so, N. Think of S as investing in sprinklers or baggage screening, and N as not doing so. Table 1 shows the payoffs to the agents in the four possible outcomes:

Table 1: Expected Costs Associated with Investing and Not Investing in Security

		Agent 2 (A_2)	
		S	***N***
Agent 1 (A_1)	***S***	$Y\text{-}c,\ \ Y\text{-}c$	$Y\text{-}c\text{-}pqL,\ \ Y\text{-}pL$
	N	$Y\text{-}pL,\ \ Y\text{-}c\text{-}pqL$	$Y-[pL + (1\text{-}p)pqL],\ Y-[pL+ (1\text{-}p)pqL]$

Here Y is the income of each agent before any expenditure on security or any losses from the risks faced. The cost of investing in security is c. The rationale for these payoffs is straightforward. If both invest in security, then both incur a cost of c and face no losses from damage so that their net incomes are $Y\text{-}c$. If A_1 invests and A_2 does not (top right entry) then A_1 incurs an investment cost of c and also runs the risk of a loss from damage emanating from A_2. The probability of A_2 suffering damage is p and the probability of this spreading is q, so that A_1's expected loss from damage originating elsewhere, i.e., "contagion" from A_2, is pqL. In this case A_2 incurs no investment costs and faces no risk of contagion but does face the risk of damage originating at home, pL. The lower left payoffs are just the mirror image of these.

If neither agent invests, then both have an expected payoff of $Y\text{-}pL\text{-}(1\text{-}p)\ pqL$. The term pL here reflects the risk of damage originating at home. The term pqL shows the expected loss from damage originating at the other agent and transferring elsewhere. This term is multiplied by $(1\text{-}p)$ to reflect the assumption that the damage can only occur once - a house can only burn down once. So the risk of contagion only matters to an agent in the case in which that agent does not suffer damage originating at home. In the sprinkler scenario this is clearly a reasonable stipulation. In the airline baggage scenario, it amounts to an assumption that one act of terrorism is as serious as several: just one will do irreparable damage to the company, so that the damages from multiple acts are not additive.

Now that the payoffs have been specified, we can ask the natural question: under what conditions will the agents invest in security? It is clear from Table 1 that for investment in security to be a dominant strategy, we need

$$Y\text{-}c>Y\text{-}pL \quad \text{and } Y\text{-}c\text{-}pqL>Y\text{-}pL\text{-}(1\text{-}p)\, pqL$$

The first inequality just says that $c<pL$, that is, the cost of investing in security must be less than the expected loss, a natural condition for an isolated agent. The second inequality is more interesting: it reduces to $c<pL- p^2qL = pL(1\text{-}pq)$. This is clearly a tighter inequality. The first inequality is what we would expect for a single agent acting in isolation and the extra term that makes the second inequality tighter reflects the possibility of contagion from the second agent. This possibility reduces the incentive to invest in security. Why? Because in isolation investment in security buys the agent complete freedom from risk; with the possibility of contagion it does not. Even after investment there remains a risk from damage emanating from the other agent. Investing in security buys you less with the possibility of contagion.

In the 2-agent problem with identical costs we can determine the optimal behavior of each agent if they both make decisions simultaneously without any communication. In this non-cooperative environment if $c < pL\,(1\text{-}pq)$, then both agents will want to invest in protective measures *(S,S)*; if $c> pL$ then neither agent will want to invest in protection *(N,N)*. If $pL<c<pL\,(1\text{-}pq)$ then there are two Nash equilibria *(S,S)* and *(N,N)* and the solution to this game is indeterminate.

These solution concepts are illustrated below with a numerical example. Suppose that $p= .1,\ q=.8,\ L=1000$ and $C= 95$. The matrix in Table 1 is now represented as Table 2:

Table 2: Expected Costs Associated with Investing and Not Investing in Security for Illustrative Example

		Agent 2 (A_2)	
		S	***N***
Agent 1 (A_1)	***S***	*Y-95, Y-95*	*Y-175,, Y -100*
	N	*Y-100, Y-175*	*Y-172, Y-172*

One can see that if A_2 has protection (*S*), then it is worthwhile for A_1 to also invest in security since its expected losses will be reduced by $pL= 100$ and it will only have to spend *95* on the security measure. However, if A_2 does not invest in security (*N*), then there is still a chance that a loss will occur to A_1. Hence the benefits of security to A_1 will only be $pL(1-pq) = 92$ which is less than the cost of the protective measure . Hence A_1 will **not** want to invest in protection. In other words, either both agents invest in security or neither of them do so. These are the two Nash equilibria.

Multiple agents

Now we move on to the more general case of an arbitrary number of agents, all symmetrically placed. Rather than two neighboring houses think of many apartment units in a building as in Scenario 2, or many airlines exchanging baggage at a large hub as in Scenario 1. What we show is that the greater the number of agents, the less the incentive for any agent to invest in security. A more formal way of saying this is that the range of values of c for which choosing to invest is a dominant strategy is reduced as the number of agents increases. In the limit as the number of agents goes to infinity then investing in security is only a dominant strategy if the cost is zero. So in the case of many agents investment in security will only occur as a result of a cooperative agreement between the agents.

We work with exactly the same framework as above, except that there are now n agents. We need to compute the risks faced by agents in this case: they obviously depend on what choices others have made. If all but one of the agents has invested in security, then the position of the remaining one is identical to his position in isolation: there is no risk of contagion. At the other extreme, suppose none of the other $n-1$ agents have invested; then the remaining agent faces risks originating at home and those originating at $n-1$ other locations.

We begin by illustrating the argument with the case of three agents, denoted A_i $i=1,2,3$. Interpret them for concreteness as apartment owners deciding whether or not to install sprinklers. How many ways can the first apartment unit (A_1) burn down if no units are protected with sprinklers? It can burn down through a fire starting internally with probability p. It can burn down through a fire at A_2 burning A_1. This event can occur with probability $(1-p)pq$. It can burn down through a fire at A_3, in two logically separate cases: apartments 1 and 2 do not burn, apartment 3 burns and the fire spreads to apartment 1. This event occurs with probability $(1-p)(1-p)pq$. And finally A_1 can burn when A_1 does not burn internally, A_2 does burn but does not cause a fire in A_1, and A_3 burns and the fire spreads to A_1. This event occurs with probability $(1-p)p(1-q)pq$). So the expected loss when none of the three apartments have installed sprinkler systems is

$$pL + (1-p)pqL + (1-p)(1-p)pqL + (1-p)p(1-q)pqL$$

which can be written as

$$pL + pqL[(1-p) + (1-p)^2 + (1-p)p(1-q)]$$

If there are four apartment units these expressions become

$$pL + pqL\left\{\begin{array}{c}(1-p)+\\(1-p)^2+(1-p)p(1-q)+\\(1-p)^3+2(1-p)^2p(1-q)+(1-p)p^2(1-q)^2\end{array}\right\}$$

which can be written as

$$pL + pqL(1-p)\left\{\begin{array}{c}1+\\(1-p)+p(1-q)+\\(1-p)^2+2(1-p)p(1-q)+p^2(1-q)^2\end{array}\right\}$$

which simplifies to

$$pL + pqL(1-p)\sum_{i=0}^{i=2}\{(1-p)+p(1-q)\}^i$$

For *n* agents this extends to

$$pL + pqL(1-p)\sum_{i=0}^{i=n-2}\{(1-p)+p(1-q)\}^i$$

The expression *[(1-p) + p(1-q)]* simplifies to *1-pq* so for the general case the expected loss is

$$pL + pqL(1-p)\sum_{i=0}^{i=n-2}\{1-pq\}^i$$

As the number of agents increase without limit this gives

$$pL + pqL(1-p)\sum_{i=0}^{i=\infty}\{1-pq\}^i$$

which simplifies to

$$pL + pqL\ (1-p)/pq = L$$

This establishes our main proposition:

Proposition 1: *When the number of agents is large and none invests in security then each agent faces a certain loss of L.*

An important corollary of this is :

Corollary 1: *When the number of agents is large then investing in security can never be a dominant strategy for any agent.*

Proof: For investing in security to be a dominant strategy it is necessary that the payoff from investing in security when no others do exceeds that from not investing in this situation. Suppose there are *n* firms in total. The payoff to firm 1 from not investing in security when the other *n-1* are also not investing is

$$Y - pL - pqL(1-p)\sum_{i=0}^{i=n-2}\{1-pq\}^i .$$

The payoff from investing is

$$Y - c - pqL\sum_{i=0}^{i=n-2}\{1-pq\}^i .$$

We omit the factor *(1-p)* when the first agent has invested in protection: there is no need to condition on the chances of agent 1 not suffering damage originating at home. Another way of seeing this is to note that *p=0* for the agent who has invested. Investing is the better strategy if and only if

$$c < pL - p^2 qL\sum_{i=0}^{i=n-2}\{1-pq\}^i$$

In the limit as $n \to \infty$ this becomes *c<0*. So investing in security will never be a dominant strategy as long as the cost of protection is positive. This completes the proof.

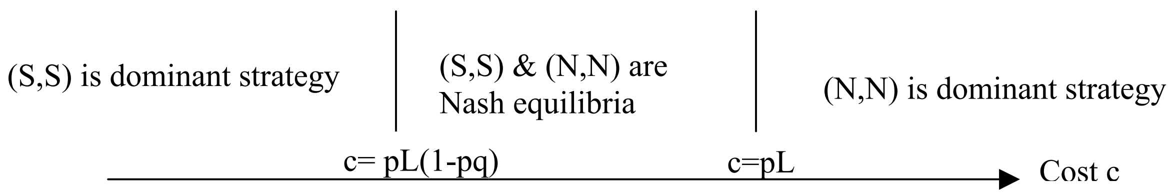
A careful examination of some of the above expressions will help clarify the intuition behind this result. Consider the expression

$$pL + pqL(1-p)\sum_{i=0}^{i=2}\{1-pq\}^i$$

for the expected loss to one of four agents when all the others have not invested in security systems and it has also decided to go unprotected. The expected loss from damage originating domestically is of course *pL,* and that from damage arising from one of the other agents is the second term. This is multiplied by *(1-p)*, because its occurrence has to be conditioned on the absence of domestic damage. Consider two apartment buildings, each of which faces a fire hazard that can cause a loss of *L* to any of the units in it. Building A has a high probability *p* of a fire occurring and Building B has a low probability *p* of the fire occurring. It is clear that each unit in Building B has a lower expected loss from domestic damage. This increases the chances of damage originating from other units and hence the expected loss from contagion for units in Building B.

Next we discuss the structure of the set of possible Nash equilibria. Return to Table 1. As we have already seen, (S,S) is a dominant strategy equilibrium if $c<pL(1-pq)$. (S,S) is a Nash equilibrium if $c<pL$, a weaker condition. (N,N) is a dominant strategy equilibrium if $c>pL$ and a Nash equilibrium if $c>pL(1-pq)$. There is an interval $pL(1-pq)<c<pL$ in which both (S,S) and (N,N) are Nash equilibria. Table 3 summarizes this information.

Table 3: Types of Nash Equilibria for Different c Values



Could there be other Nash equilibria in this game? The answer is no, at least as long as all agents are identical: for ((N,S) to be an equilibrium it is necessary that $Y-pL>Y-c$ or $c>pL$ and also $Y-c-pqL>Y-pL-(1-p)pqL$ or $c<pL(1-pq)$ which is obviously impossible. So in the two-agent case the only equilibria are where both agents invest or both do not invest. Does this change as the number of agents increases? We conjecture that it does not, and that even with many identical agents, they all will choose the same strategy at a Nash equilibrium.

Note that in the two-agent case, if the agents have different costs of investing in security measures, then we may find an equilibrium at which one invests and the other does not. Specifically, let c_1 and c_2 be the costs of the two agents: then (N,S) will be a Nash equilibrium if $c_1>pL$ and $c_2<pL(1-pq)$. This requires that the two costs differ by at least p^2qL.

There are three critical values of *c* that need to be considered in determining the nature of the equilibria when there are *n* agents in the system. Let c^{**} represent the value of *c* above which all agents will **not** want to invest in protection. If there are no externalities and all the benefits of protection are captured by each agent then $c^{**}=pL$. This value of c^{**} is invariant to the number of agents in the system. Let $c^*(n-1)$ represent the value of *c* below which an agent will want to invest in security if all other *n-1* agents are unprotected. For the model above $c^*(n-1) = pL - p^2q\Sigma(1-pq)^i$.

We can now extend the 2-agent case to an n-agent example, where *n* varies from 1 to10, using the same values of $p=0.1$, $q=0.8$ and $L=1000$ but not specifying the value of *c*. Figure 1 depicts the three ranges of *c*: Range 1 is where there is only one Nash equilibrium (N,N,.....N) so that no agent will want to invest in security (i.e. $c>c^{**}$) ; Range 2 also has one Nash equilibrium (S,S,.... S), so that all agents will want to undertake protection [i.e. $c < c^*(n-1)$]. When $c^*(n-1) \leq c \leq c^{**}$ then we are in Range 3 where there are two Nash equilibria (S,S....S) and (N,N....N). In this case some type of public sector intervention or coordinating mechanism is necessary if one wants to ensure that agents arrive at the equilibrium where they invest in protection.

Turning to Figure 1, we see that whenever $c>c^{**}=100$ then the only Nash equilibrium is (N,N....N) and none of the agents will want to invest in protection. Turning to the other two ranges, if all the other 9 agents have protected themselves, then $c^*(0)= 100$ and the remaining agent will want to invest in protection if $c<100$. On the other hand, if none of the 9 other agents have adopted a protective measure then $c^*(9)=47.2$ and the remaining agent will only consider purchasing protection if $c<47.2$. For the 10-agent case Range 3 consists of all values between 47.2 and 100. Only when $c<47.2$ will (S,S.... S) be the only Nash equilibrium (Range 2).

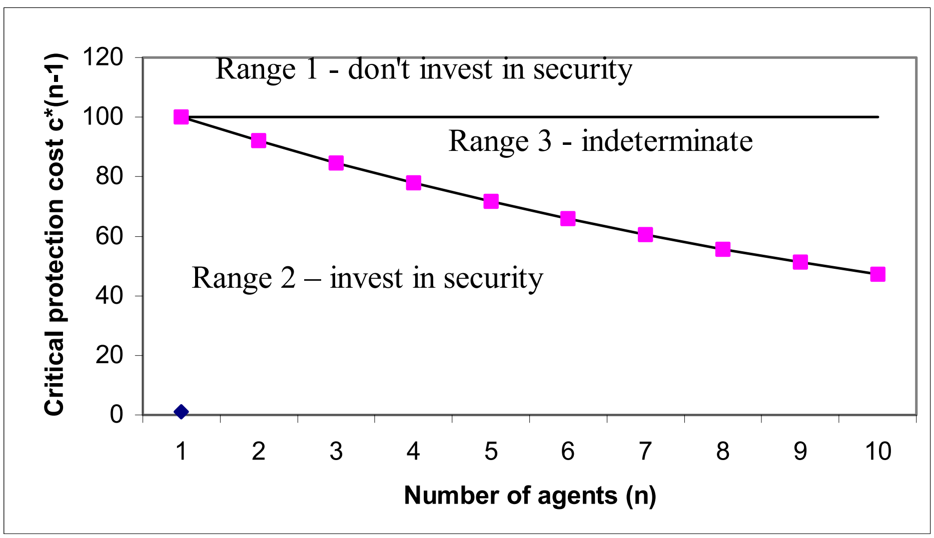


Figure 1: Relationship Between Cost of Protection (c) and Decision on Whether to Invest in Protection as Number of Agents (n) Changes.

Since in our model there is no possibility of contamination by someone who has adopted protective measures, the only parameter that could change the choice of an agent who has selected N is the number of agents who have not adopted the security measure. Thus from the perspective of an agent who has not invested in security and wants to know the critical cost for investing, an 11 agent problem where 2 people have adopted security measures is equivalent to a 10 agent where 1 person has adopted the measure or a 9 agent where noone has adopted the measure.

Implications of the Solution

The problem of encouraging individuals to adopt protective measures resembles the prisoner's dilemma problem in the sense that it is often advantageous for all agents to adopt protection for both themselves and society, but none of them have an economic incentive to do so on their own**.** A classic prisoner's dilemma is where each firm has a cost incentive to undertake some activity (e.g. polluting the environment). It knows that if there were a coordinating mechanism so that none of them engaged in this activity, they would all be better off economically and social welfare would also be improved. (e.g. firms' profits would be higher and the air and/or water would be cleaner.)

For certain cost structures the interdependent security problem has the same characteristics as a prisoner's dilemma. More specifically if $pL < c$ then each agent prefers not to invest in security [i.e. (N,S) 〉 (S,S) for agent 1 and (S,N) 〉 (S,S) for agent 2] leading to a single Nash equilibrium at (N,N) . However, if $pL + (1-p)pqL > c$ then both agents would be better off at (S,S) than at (N,N).

For other situations where $pL>c$ but $c>pL(1-pq)$ as illustrated in Table 2, the interdependent security problem differs from the prisoner's dilemma, since the agents are in Range 3 where there are two Nash equilibria (S,S) and (N,N). Now if one can convince one agent to invest in security, there will be an economic incentive for the other agent to voluntarily follow suit. In the context of multiple agents, consider the two scenarios at the beginning of the paper. BC Airlines is more likely to invest in a baggage checking system if it knows that some of the other airlines have taken this step. The Green family's decision on whether to invest in a sprinkler system depends on how many other units in the apartment have taken similar action. In each case the decreased likelihood of contagion as more agents are protected, increases their willingness to pay for the protective measure. Their risk is now more under their own control and more affected by their investment in security. The challenge is how to internalize the externality for some or all the agents, so a typical agent is willing to invest in security.

3. Internalizing Externalities

The only ways to encourage agents to invest in security when they face the possibility of contamination from others is to develop a set of economic incentives (either positive or negative) that makes it more attractive for some or all of the involved individuals to take protective actions. Below we examine a set of different measures ranging from private market mechanisms to regulations to collective choice that may internalize the externalities associate with protective measures where there are interdependencies between agents.

Insurance

Insurance appears to be a logical way for encouraging security since it rewards individuals who adopt protective measures by reducing their premium to reflect the lower risk. However, in order to deal with the externalities created by others who do not invest in protection, the agent causing the damage must be forced to pay for the losses. If a fire spreads from apartment 2 to apartment 1, then apartment 2's insurer would have to pay for the cost of the damage to 1.

This is not how current insurance practices operate for any type of risk. An insurer who provides protection to A_1 is responsible for all losses incurred by agent 1 no matter who caused it as long as this risk is covered in the policy.[1] Hence as the number of unprotected agents that can contaminate A_1 increases, the smaller the premium reduction that an insurer can offer agent 1 for investing in a protective measure. One reason for this contractual arrangement between insurer and insured is the difficulty in assigning causality for a particular event. The real world is considerably more complex than our highly simplified fire scenario and it would be difficult to know what actually caused a fire in any apartment unit.

Interestingly enough a monopolistic insurer would want to internalize the externality if it was providing coverage to all agents. An agent who adopted a protective measure would be provided premium reductions not only for the reduced losses to its own unit but also for the reduction in losses to others. Social insurance programs have the advantage over a competitive insurance market in encouraging this type of protection. In the above example, as long as $c < pL$, there would be an incentive for all agents to invest in security and the Nash equilibrium would be (S,S.....S).

Liability

If an agent who caused damage to other agents through not adopting a protective measure was held liable for these losses, then the legal system would offer another way for internalize the externality due to interdependent security. We do not know of any cases where an agent has been held liable for the damages to another agent because it did **not** invest in protection. In the case of the airline example, it would be difficult to know whether an unchecked bag from another airline caused damage to the plane or whether it was due to one of BC Airline's own bags. Similarly if a fire occurred in the Green unit, it would be difficult to know whether it was caused by a fire spreading from another unit because it did not have a sprinkler system or it was due to a faulty sprinkler system in the Green apartment. The costs of settling these disputes appear to favor a liability system where each agent is responsible for its own losses unless there is a clear case of negligence on the part of some unit.

Taxation

A more direct way of encouraging greater security is to levy a tax of t dollars on any entity that does not invest in protection. In the case of identical agents one would want the tax to be high enough so that it is cost effective for everyone to take this action and the only Nash equilibrium would be (S,S....S). The magnitude of the tax depends on how many agents are in the pool and the cost of protection, c.

Suppose that there are n agents in the pool and none of them have invested in security. The government wants to determine the minimal tax t^* to induce each agent to protect

[1] If the damage from an insured risk is due to negligence or intentional behavior then there are normally clauses in the insurance policy that indicate that losses are not covered (e.g. a fire caused by arson).

itself. As shown in section 2 if an agent invests in protection then its cost will be

$$c + pqL \sum_{i=0}^{i=n-2} \{1 - pq\}^{i}$$

Let

$$M = pqL \sum_{i=0}^{i=n-2} \{1 - pq\}^{i}$$

so that the cost is $c+M$. Note that M reflects the negative externalities to an agent from contamination due to others not protecting themselves. If an agent does not invest in protection and is taxed t dollars, its cost will be

$$pL+(1-p)M+t$$

Hence for any agent to want to invest in protection when no one else does, the tax must be high enough so that

$$t > c- p(L- M)$$

If $c \leq p(L- M)$ then the cost of protection is sufficiently low that there is no need to impose any tax on an agent for it to want to invest in protection. Hence

$$t^*= max \{0, c-p(L- M) \}$$

Consider the illustrative example depicted in Figure 1 where n=10. If t=0, then an agent will only want to invest in security if no one else does when $c< p(L- M)= 47.2$. If c> 47.2, then t*= c-47.2.[2] Note that a subsidy on protective measures plays the identical role in inducing agents to invest in security, as does a tax, except that now the cost c is reduced so that the protective measure is more attractive to the agent.

Regulations and Standards The possibility of contamination by other units provides a rationale for well-enforced regulations and standards that require individuals and firms to adopt protective mechanisms. The need for baggage check-in systems took on greater

[2] Suppose that c>c** so that there is no incentive for any agent to invest in protection even if all other n-1 agents have protected themselves. If there are additional indirect benefits from protection besides a reduction in the expected loss (pL), then the government may want to impose a tax on unprotected agents that is high enough to induce everyone to protect themselves.

importance after the Sept. 11th tragedies and has led the government to require them by the airlines. The U.S. Congress now requires all airlines to have a checked baggage security program to screen all bags for bombs (NY Times 2002).

Building codes for reducing damage from natural disasters are standard in most hazard-prone states and can be justified in part by the externalities associated with damage from a disaster [Cohen and Noll 1981; Kleindorfer and Kunreuther (1999)]. When a building collapses it may create externalities in the form of economic dislocations and other social costs that are beyond the economic loss suffered by the owners. These may not be taken into account when the owners or developers evaluate the importance of adopting a specific mitigation measure.

Coordinating Mechanisms One way to convince the *n* independent agents that it would be in everyone's best interests to invest in protection is to utilize some official organization to coordinate these decisions. For example, the International Air Transport Association (IATA), the official airline association has indicated on its WEB site that since Sept. 11th they "have intensified hand and checked baggage processing". IATA could have made the case to all the airlines that they would be better off if each one of them utilized internal baggage checking so that the government would not have had to require this. In the case of the fire sprinkler example, the developer of the apartment could try and convince owners of individual units that it would be in their best interest to invest in a sprinkler system, because if everyone does the insurance premium reductions could justify the investment.

An association can play a coordinating role by stipulating that any member has to follow certain rules and regulations including the adoption of security measures and has the right of refusal should they be asked to do business with an agent that is not a member of the association and/or has not subscribed to the ruling. IATA could require all bags to be reviewed carefully and each airline could indicate that it would not accept in-transit bags from airlines that did not adhere to this regulation.

Apparently this is done by IATA agreements regarding pricing policies. If an airline does not belong to IATA and you want to transfer to this airline from an originating airline that is part of IATA, the originating airline will not make a reservation for you (e.g. United will not make a reservation for you to fly from Hong Kong to Bangkok on Thai Airlines if your originating flight is from LA to Hong Kong). Furthermore an IATA airline will not honor a non-IATA airline ticket unless it conforms to the IATA tariff conference (e.g. US Air would not honor a Jet Blue airline ticket).[3]

Such a system might be applicable to jointly owned property such as co-op apartments in NYC. Here a rule could be passed by the governing board that a prospective buyer would not be allowed to purchase a unit unless he or she agreed to undertake certain loss reduction measures such as installing fire prevention equipment and smoke alarms.

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3 See the IATA web site at http://www.iata.org/membership/steps.asp#10

On a more informal level it might be possible to establish social norms by individuals or organizations feeling pressure from others to invest in protection (Sunstein 1996). This is not easy to do since there are normally no visible benefits from the investment until a disaster occurs. To the extent that opinion leaders can convince others in their community that these investments will yield expected benefits to everyone in the form of lower losses and higher property values such a strategy may work.[4]

Peace of Mind

In the model considered above there were no internal positive effects associated with protective measures. Many individuals invest in security to relieve anxiety and worry about what they perceive might happen to them. They may be prepared to protect themselves and their family in order to gain peace of mind. Of course, if they become aware that they may suffer substantial losses from others who are unprotected, then this new knowledge may increase their anxiety while at the same time showing that investing in these protective measures has more limited benefits than if they were not open to contamination by others.

4. Relationship to Other Forms of Protection

The problem of interdependent security implies that the risk is such that the state of nature (e.g. occurrence of a fire) can cause losses not only to the agent where it originates but to other agents as well. Hence protection by one agent can reduce the chances of contamination of another agent. In this section we examine risk reduction measures against other hazards, theft protection and vaccinations, to determine their similarities and differences from protection against interdependent security risks.

Theft Protection

Consider the case where a burglar is considering which one of a set of identical houses in a neighborhood to rob. His concern is the chance of being caught in attempting to break into the house. By installing a burglar alarm you increase the chance that the intruder will be detected. If you announce publicly (with a sign) that your house has been protected, then the burglar will look for greener pastures to invade. In other words, installing a burglar alarm in your house decreases the chances that your house will be robbed and increases the chance that other unprotected homes will be a target for the thief.[5]

Let p = probability of a loss (L) to any house when none of the homes in the area have invested in protection. For example, if a thief would randomly choose one of the n houses in the area as a target, then $p = 1/n$. Now suppose that you purchase a burglar alarm that can always detect a thief should he attempt to break into your house and you publicize that you our house is protected in this way. The risk of a loss to your house is now 0 independent of what other houses have done. In other words, there is no possible

[4] See Ostrom (1990), particularly chapter 6 that deals with the conditions under which norms evolve governing the use of common property resources.
[5] We appreciate a helpful discussion with Daniel Kahneman on this point

contamination from other houses in the area as in the interdependent security problem. In fact, there is now an increase in the probability that one of the other houses in the neighborhood will be robbed. Let p' represent this revised probability of a theft with $p' > p$. In the case of random theft, your house is off-limits and the other $n-1$ houses face a risk of $p' = 1/n-1$ of being burglarized.

If all homes are identical then there will be two Nash equilibria just as in the interdependent security problem but the solution is much more straightforward because there is no contamination. If the cost of the burglar alarm is c and individuals are risk neutral then no one will invest in a burglar alarm if $c > pL$. If $c < pL$ then everyone will want to protect themselves.

The more interesting case occurs when there are perceived differences in probability of a theft. Suppose that the perceived probability by agent i of a theft is p_i and that the agents are ordered so that agent 1 has the highest probability, agent 2 the next highest, and agent n the lowest probability p_n . Losses from theft are still assumed to be L. In this case if agent 1 finds that $p_1 L > c$, he will invest in protection. Now the remaining agents perceived probability of a theft will be increased and agent 2 as well others may decide to invest in a burglar alarm system. The process continues until either all agents invest in burglar alarms or there is no incentive for some of the agents to take this protective action even when their probability of a theft has increased due to others undertaking security measures.

A prescriptive implication of this finding is that neighborhoods and local police have incentives to form associations that discourage burglars from selecting their area as a target. The announcement that homes in a particular neighborhood that have joined Operation Identification where their goods are marked and can be discovered by the local police is an example of this type of activity. Neighborhood crime watches are another way to reduce the chances that burglars will select your area.

Vaccinations

The interdependent security problem also has similarities to, and differences from, problems raised by vaccination. Clearly there are externalities here: if I am vaccinated against a disease, you will not catch it from me. So one person investing in protection conveys positive externalities on others, as in the problems discussed in this paper. This much is common to both issues.

Consider however the Nash equilibria that may arise when people are choosing whether or not to be vaccinated. Suppose that tomorrow an effective vaccine against influenza is approved for general use. When choosing whether to be vaccinated or not, each person has to anticipate the choices of others. If everyone else were to be vaccinated, then there would be no point in my being vaccinated, as I would be in no danger of catching the flu. At the other extreme, if I believed that most people would not be vaccinated, this would increase my incentive to be vaccinated. From this we can see that if the vaccination cost is sufficiently low and the risk is sufficiently high then a situation where no one is vaccinated cannot be a Nash equilibrium.[6]

On the other hand, everyone being vaccinated is also not a Nash equilibrium, for if I believe that everyone else will get vaccinated then I will not want to be vaccinated. If there is a Nash equilibrium here, it is probably in mixed strategies, with everyone choosing a certain probability of being vaccinated. Clearly then the equilibria that arise when people are choosing whether or not to be vaccinated are quite different from those that arise when they are choosing whether or not to invest in interdependent security devices.

5. Future Research

The decision as to whether one wants to undertake protection against events where there is interdependence between your actions and those of others raises a number of interesting theoretical and empirical questions. We discuss some of these issues in this section.

Differential Costs and Risks

The nature of stable Nash equilibria for the problems considered above and the types of policy recommendations may change as one introduces differential costs across the agents who are considering whether or not to invest in security.

Consider the set of apartment owners in a building, each deciding whether to invest in a fire protection system. As pointed out in Section 2, if there are differential costs and/or risks between units, we would expect to find a stable Nash equilibrium that consisted of a combination of S's and N's. Some agents would have low enough costs that they would want to invest in the protective measure while others would find it too expensive.

One needs to reexamine the types of prescriptive recommendations for dealing with the issue of differential risks and/or costs. For example, suppose that some apartment owners had a greater chance of contaminating others because of their location in the building. Should one tax them more if they do not invest in a sprinkler system? If differential taxation is not feasible for political reasons should one resort to well-enforced building codes or other regulations to deal with the interdependent security problem?

Multi-Period and Dynamic Models

The decision on whether or not to invest in security normally involves multi-period considerations since there is an upfront investment cost that needs to be compared with the benefits over the life of the protective measure. A property owner who invests in a sprinkler system knows that it will offer benefits for a number of years. Hence one needs

[6] See Hershey et al (1994) for a more detailed discussion of the role that free riding, and bandwagoning play in vaccination decisions.

to discount these benefits by an appropriate interest rate and specify the relevant time interval in determining whether or not to invest in these actions. There may be some uncertainty with respect to both of these parameters.

From the point of view of dynamics, ones own decision on whether to incur a cost of protection will depend on how many others have taken similar actions. How do you get the process of investing in security started? Should one subsidize or provide extra benefits to those who are willing to be innovators in this regard to encourage others to take similar actions? In order to answer these and other questions one needs to develop sequential models of decision-making. These models will need to consider the special characteristics of the hazard and the nature of the contamination effects. A dynamic model for fire protection will have a different set of interactions than one for theft protection or immunization against specific diseases. The policy recommendations will also reflect these differences.

Behavioral Considerations

The models we have developed on interdependent security as well as theft and vaccine protection all assumed that individuals made their decisions by making tradeoffs between the expected benefits to them with and without protection and the costs of investing in security. We will label this a *rational model* of behavior

There is a growing literature in behavioral economics that suggest that individuals make choices in ways that differ from the rational model of choice. [Kahneman and Tversky 2000]. With respect to protective measures there is evidence from controlled field studies and laboratory experiments that many individuals are not willing to invest in security for a number of reasons that include myopia, high discount rates and budget constraints. (Kunreuther, Onculer and Slovic 2000). On the other hand there are those who want to invest in protection in order to reduce their worries and concerns (Baron, Hershey and Kunreuther 2000).

A more realistic model of interdependent security that incorporated these behavioral factors as well as misperceptions of the risk may suggest a different set of policy recommendations than would be implied by a rational model of choice. For example, if agents were reluctant to invest in protection because they were myopic, then some type of loan tied to their mortgages may enable them to see the long-term benefits of the protective measure. A long-term loan would also help relieve the budget constraints that may deter some people or firms from incurring the upfront costs of the risk-reducing measure.

Future Empirical Studies

The issues discussed above suggest a number of empirical studies on issues associated with interdependent security. Given the concern with terrorism both in the United States and the rest of the world it would be interesting to undertake studies so one can learn more about the factors which are leading some organizations to invest in security and why others are deterred from doing so. What actions can the public sector take in encouraging property owners and organizations to invest in certain protective measures and refrain from doing so with others? What are the appropriate roles of taxation, regulations and standards (e.g. well-enforced building codes)? How can market mechanisms such as insurance, bank loans and potential liability aid in this process?

What institutional mechanisms would aid the decision process of agents on protective measures when others will be affected? Can industry associations like IATA for the airlines play an important role in facilitating actions by individual companies? What types of property rights would encourage agents to undertake security measures? For example, Turkey requires unanimity from all their apartment owners before any protective measure can be implemented in the building. New York City Coop apartments normally have a governing board that proposes rules and regulations for the building and then majority rule determines whether they are ratified.

Concluding Comments

The events of September 11th have highlighted the importance of addressing the questions associated with interdependent security. This paper should be a viewed as a first step in providing a framework for undertaking future theoretical and empirical studies in this area. By developing a richer set of models and testing them through controlled experiments and field studies we are hopeful that a viable set of policies will emerge for dealing with the challenges we face today in dealing with hazards where there are risks of contamination.

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