The problem of prevention

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Abstract

Many disasters are foreshadowed by insufficient preventative care. In this paper, we argue that there is a true *problem of prevention,* in that insufficient care is often the result of rational calculations on the part of agents. We identify three factors that lead to dubious efforts in care. First, when objective risks of a disaster are poorly understood, positive experiences may lead to an underestimation of these risks and a corresponding underinvestment in prevention. Second, redundancies designed for safety may lead agents to take substandard care. Finally, elected officials have an incentive to underinvest in prevention for some disasters, especially those that are relatively unlikely.

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A remarkable number of disasters and near-disasters, from the nuclear mishap at Three Mile Island,[1] to the Union Carbide plant tragedy in Bhopal,[2] to the Challenger disaster,[3] to Hurricane Katrina[4] have been preceded by a woefully inadequate level of preventative care, making these adverse events not so much manifestations of poor luck, as all but inevitable occurrences. Indeed, the phrase "an accident waiting to happen" has become somewhat of a cliche in post-event reporting. In this paper, we argue that there is a true *problem of prevention,* in that many accidents are waiting to happen as the result of rational calculations on the part of agents. We identify three factors that lead to dubious efforts in care.

1. When objective risks of a disaster are poorly understood, positive experiences may lead to an underestimation of these risks and a corresponding underinvestment in prevention.

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[1] In March 1979, there was a partial meltdown of the reactor core of the Three Mile Island Unit 2 nuclear power plant.

[2] In December 1984, methal isocyanate gas was released at the Union Carbide chemical plant in Bhopal, India, resulting in thousands of deaths and hundreds of thousands of injuries.

[3] The American space shuttle Challenger exploded shortly after takeoff on January 28, 1986.

[4] Hurricane Katrina struck southeast Louisiana on August 29th. Considerable damage was caused, including the flooding of 80% of New Orleans.

2. Redundancies, designed for safety, may lead agents to take substandard care.
3. Elected officials have an incentive to underinvest in prevention for certain disasters – in particular, for those that are relatively unlikely.

Some or all of these factors may be present in any given situation. Rather than present a grand model which incorporates all three elements, we present three related models. This permits us to focus sharply on the different effects.

Much of the writing on accidents comes from sociologists and psychologists. In particular, Vaughan (1996) has written an in-depth study of the Challenger accident in which she faults the "culture" of organizations, in general, and of NASA, in particular; Perrow (1999) has written about the danger of tightly coupled complex systems, such as Three Mile Island; Reason (1990) has examined the types of errors made by humans, and their causes. We will return to this literature, and to the relevant economics literature, at various points in the paper.

1 Good News Can Be Bad

The world is a risky place, but how risky is a matter of some choice. Safeguards and redundancies can be built into nuclear power plants, planes can be extensively tested and regularly inspected, space shuttle flights can be cancelled if weather conditions are poor. Just how much effort and expense should be put into preventative care? Among other things, this depends upon the inherent riskiness of the activity involved. But how are the relevant probabilities to be determined?

Scientific and engineering considerations yield a priori probability estimates, which must then be updated in the light of experience. Some industries, such as the airline industry, have a long track record with both successes and failures, so that there is a good understanding of the pertinent probabilities — even when new engines and airplanes are developed, there is a good understanding of the ways in which these need to be tested. Other enterprises, such as nuclear power plants and the space shuttle, involve relatively new technologies with limited experience. These spare histories make it very difficult to estimate the risks involved. In particular, unbroken strings of success make it difficult to assess the probability of a failure. As an example, the space shuttle Challenger had been preceded by twenty-four successful shuttle launches without a failure, and estimates of a catastrophic failure ranged from 1 in 100 to 1 in 100,000 (Feynman (1988))[5]. Similarly, prior to the incident at Three Mile Island there had not been a single accident at a commercial nuclear power plant, and the risks were poorly understood.

Abstractly speaking, any reasonable updating process has the feature that the more time that passes without an adverse incident, the lower the probability that is attached to one. This increasing optimism will lead to a declining investment in precautionary care (under reasonable conditions), and, eventually, to dangerously little care. In this respect, good news can be bad. Investigations into the meltdown at Three Mile Island and the space shuttle Challenger accident show that such optimistic underinvestment is precisely what took place. With regard to the former, the Kemeny Commission (1979) concluded that:

[5] It should be noted, however, that the (management) estimate of 1 in $100,000$ is a little hard to rationalize.

"After many years of operation of nuclear power plants, with no evidence that any member of the general public has been hurt, the belief that nuclear power plants are sufficiently safe grew into a conviction. One must recognize this to understand why many key steps that could have prevented the accident at Three Mile Island were not taken. (p.9)."

With regard to the latter, as part of the investigating commission, Feynman (1988)[6] wrote:

> We have also found that certification criteria used in flight readiness reviews often develop a gradually decreasing strictness. The argument that the same risk was flown before without failure is often accepted as an argument for the safety of accepting it again. (p.220)
>
> The *Challenger* flight is an excellent example: there are several references to previous flights; the acceptance and success of these flights are taken as evidence of safety. (p223)
>
> The slow shift toward a decreasing safety factor can be seen in many [areas]. (p230)

Vaughan (1996) has termed this steady decline in standards the "normalization of deviance." We now proceed to a formal model of this phenomenon. To fix our ideas, consider a machine consisting of a single part that may become defective and fail in any period with some fixed unknown probability. In each period, prior to running the machine the part can be tested and, if found defective, costlessly repaired. The test itself, however, is costly and imperfect – at higher costs the test is more likely to detect a defect. We can think of a defective part as an *event*, which turns into an *accident* if and only if it is not detected. With this story in mind, consider the following simple model.

In each period $t = 0, 1, 2...$, nature chooses $y \in \{e, n\}$ (an event occurs or no event occurs) according to some probability $\Pr(y = e) = \hat{\theta} \in (0, 1)$. The parameter $\hat{\theta}$ is unknown, and a decision maker has a belief about $\hat{\theta}$ given by a probability distribution p over $[0, 1]$. For each belief p, the subjective probability of an event is denoted

$$\widehat{p} = \int \theta dp(\theta).$$

An event may or may not turn into an accident. An accident causes a loss of D (in present value terms); the payoff in any single period in which there is no accident is normalized to zero. In each period, the agent can invest in preventative care, which reduces the likelihood of an event turning into an accident. Specifically, the subjective probability of an accident is given by $\phi(\widehat{p}, \cdot) : \mathbf{R}_+ \to [0, \widehat{p}]$, which is continuous and weakly decreasing for all $\widehat{p}$. For an

[6] Feynman's appendix to the commission's report is reprinted in Feynman (1988).

investment c in preventative care, we have[7]:

Probability	Outcome
$\phi(\widehat{p}, c)$	event and accident
$\widehat{p} - \phi(\widehat{p}, c)$	event, but no accident
$1 - \widehat{p}$	no event, no accident

The agent discounts at a rate $\delta \in (0,1)$. Given a prior p, let p_n and p_e denote the (Bayesian) posterior beliefs after no event has happened and after an event has happened, respectively. Starting from a belief p, the Bellman equation for this problem is

$$\begin{aligned} v(p) &= \max_c \{\phi(\widehat{p}, c)[-D + \delta v(p_e)] + [\widehat{p} - \phi(\widehat{p}, c)]\delta v(p_e) + (1-\widehat{p})\delta v(p_n) - c\} \\ &= \max_c \{-\phi(\widehat{p}, c) D + \widehat{p}\delta v(p_e) + (1-\widehat{p})\delta v(p_n) - c\} \end{aligned}$$

In each period, the decision maker's problem is two-fold: to first determine an updated belief p in light of the previous period's experience, and to then choose the optimal c.

The following proposition shows that, quite naturally, the subjective probability that an event will occur falls following no event.

Proposition 1 *For any density p with support $[0,1]$, the probability of an event under beliefs p_n is strictly smaller than under beliefs p. That is,* $\widehat{p}_n \equiv \int_0^1 \theta p_n(\theta)\,d\theta < \int_0^1 \theta p(\theta)\,d\theta = \widehat{p}$.

Proof. All proofs are in the appendix. ■

Thus, a string of periods with no events leads to a reduced belief in the probability of an event.[8]

Although the Kemeny commission and Feynman appear to take it for granted that increasing optimism leads to declining care, it is easy to think of scenarios in which the reverse is true. Nonetheless, the next proposition supplies plausible conditions under which their intuition is correct.

Proposition 2 *Suppose that ϕ is twice continuously differentiable, with $\phi_{22} > 0$ and $\phi_{12} < 0$. Then, for each $\hat{p}$, the optimal c, $c(\hat{p})$, is unique. Furthermore, $c(\hat{p}_n) < c(\hat{p})$, for all $\hat{p}$, whenever $c(\hat{p}) > 0$.*

Propositions 1 and 2 together imply that a string of successes will lead to declining levels of care. This decline corresponds to the "normalization of deviance" noted by Vaughan. However, despite the pejorative term "deviance", the question remains as to whether or not this decline in the level of care is proper; after all, it is the result of Bayesian updating. Absent an objective measure of the probability of an accident, the question cannot

[7] The formulation below captures many possibilities. For instance, the probabilities of an event with an accident and of an event without an accident could be of the form $\hat{p}f(c)$ and $\hat{p}(1-f(c))$, respectively, so that $\phi(\widehat{p}, c) = \hat{p}f(c)$.

[8] Any reasonable updating procedure, not just Bayesian updating, will have the feature that a string of n's leads to an increasing belief in the likelihood of an n, so that the conclusion of Proposition 1 is quite general.

be definitevely answered. Nonetheless, it is clear that both the Kemmeney Commision and Feynman considered that a) at the time of the accident, agents were taking too little care, while b) initially they were taking the correct (or at least a reasonable) amount of care.

To understand this attitude, let us think of those who set the care standards to be, collectively, the principal, and those who actually take the care to be, collectively, the agent. We then have a principal-agent problem.[9] In a standard principal-agent problem, the "problem" arises from the fact that the principal and agent have different motivations. Here, we focus on a different problem, namely one that arises from a discrepancy in the beliefs of the principal and the agent. We call this type of problem a *belief-based agency problem*.[10]

The basic idea in the present context is the following. The principal is an expert who conveys her information/beliefs to the agent, but (inevitably) does so imperfectly. While the principal may be able to convey her mean belief fairly accurately, she is unable to convey the breadth and depth of the information on which this belief is based. As a result the agent reacts more to additional information, such as good experience, than the principal deems optimal.

Formally, suppose the principal and agent seek to maximize $\{-\phi(\widehat{p}, c) D + \widehat{p}\delta v(p_e) + (1-\widehat{p})\delta v(p_n) - c\}$ and $\{-\phi(\widehat{q}, c) D + \widehat{q}\delta v(q_e) + (1-\widehat{q})\delta v(q_n) - c\}$, respectively, where $\hat{p}$, p_e, and p_n are derived from the principal's belief p, while $\hat{q}$, q_e, and q_n are derived from the agent's belief q. Both p and q are assumed to be represented by Beta distributions.[11] The Beta assumption is fairly unrestrictive, as any smooth unimodal density on $[0,1]$ can be well approximated by a Beta density (Lee (1989)). Statisticians often posit a Beta distribution when studying the updating of Bernoulli priors.

First suppose that the distributions of the principal and the agent have the same mean, but that the agent's distribution has a larger variance. Then, initially, the principal and the agent agree upon the optimal amount of care. However, as we show below, following any sequence of non-events, the agent is always more optimistic than the principal, and, hence, invests too little in care. In fact, we establish a more general result. To understand this result, first note that given two Beta distributions $B(a,b)$ and $B(d,e)$ with the same mean, it can be shown that $B(a,b)$ has a larger variance than $B(d,e)$ if and only if $a < d$ and $b < e$. We generalize this condition and say that the beliefs of an agent with prior $B(a,b)$ are *more disperse* than those of a principal with prior $B(d,e)$ if $a < d$ and $b < e$ (thus, we have removed the requirement of equal means).

If the agent's beliefs are more disperse than the principal's, then initially the agent may be either more or less optimistic, in terms of mean belief, than the principal. In either case, as the following proposition indicates, following enough good news, the agent will be more optimistic than the principal (and underinvest relative to the principal's optimum).[12]

[9] Of course, implicit in the problem is the presumption that the principal cannot simply take the care herself, and cannot adequately monitor the agent's actions.

[10] Many public health campaigns surrounding lifestyle choices (such as the use of condoms, the decision to smoke, dietary choices) fall into this category: The government seeks to change behaviour by informing citizens of the risks involved, but typically finds that individuals' beliefs concerning these risks can only be influenced, not dictated.

[11] The Beta distribution $B(\alpha+1, \beta+1)$ has a density on $[0,1]$ given by $f(x) = x^{\alpha}(1-x)^{\beta} / \int u^{\alpha}(1-u)^{\beta}\, du$, and a mean of $\frac{\beta+1}{\alpha+\beta+2}$. Moreover, after an observation of an event, a prior $B(\alpha+1, \beta+1)$ is updated to $B(\alpha+1, \beta+2)$ and after a non event it becomes $B(\alpha+2, \beta+1)$.

[12] Loosely speaking, the agent learns more from the positive signals than the principal does. The problem

Let p_{n^t} (resp., q_{n^t}) be the (Bayesian) posterior of p (resp., q) following t observations of n, and recall that $\widehat{p}_{n^t}$ (resp., $\hat{q}_{n^t}$) is the estimated probability of an event based on the distribution p_{n^t} (resp., q_{n^t}).

Proposition 3 *Suppose the beliefs of the agent, q, are distributed according to $B(a,b)$ and the beliefs of the principal, p, are distributed according to $B(d,e)$. If the beliefs of the agent are more disperse than those of the principal, then, for all*

$$t > \max\left\{\frac{bd-ae}{e-b}, 0\right\} \equiv T^*$$

we have $\widehat{q}_{n^t} < \widehat{p}_{n^t}$. If $\Phi_{22} > 0$, $\Phi_{12} < 0$, and $c(p_{n^t}) > 0$, then, $c(q_{n^t}) < c(p_{n^t})$ for all $t \geq T^*$.

When the potential damage from an accident is very large, the optimal number of accidents is close to zero. For this reason, nuclear reactors are built so that a string of successes is the norm. Unfortunately, our results indicate that this success is to some extent self-defeating.

The Kemeny Commission was well aware of the danger of "overupdating" on the part of power plant operators. In its report it states:

> The Commission is convinced that this attitude [namely, the inference that nuclear plants are safe based on their positive record] must be changed to one that says nuclear power is *by its very nature* potentially dangerous, and, therefore, one must continually question whether the safeguards already in place are sufficient to prevent major accidents (emphasis added). (p9)

In effect, the commission is imploring nuclear operators to ignore favorable experience pointing to the safety of nuclear plants. Some of Feynman's recommendations can similarly be interpreted as exhortations to downplay the significance of experience. However, it is difficult, if not impossible, to prevent agents from engaging in their own updating. Moreover, at least two factors exacerbate this difficulty. The first one is the presence of idiosyncratic differences. Consider airplane pilots. It is only natural, though perhaps unfortunate, for a particular pilot without an adverse incident to think of himself or herself as particularly skilled, and to be correspondingly less wary than overall probabilities would recommend. Similarly, operators at nuclear power plants may well feel that general experience at plants does not account for the specific conditions at their specific plants. The second one is the phenomenon that, as the availability heuristic teaches, when estimating probabilities people place undue weight on factors that they can readily recall, chief among these being their own experience.[13]

Proposition 3 affords another interpretation. Airplanes are well understood, not only because of their long experience, but also because they are built "bottom up." In contrast with conventional aircraft, the space shuttle was built with a "top down" approach (Feynman

of which priors are subject to more learning has not, as far as we know, been studied in general.

[13] Naturally, our results suggest a line of research into the optimal incentive schemes for belief-based agency problems. We do not pursue such an investigation in the present paper, where we merely elucidate the nature of the problem.

(1988)), making it difficult to obtain a tight estimate of the safety of its novel technology. Let the priors p correspond to well-established and time-tested technologies, and the priors q correspond to new or inovative technologies for which less is known. With that reading, Proposition 3 tells us that innovative technologies are especially susceptible to good news being bad.

We turn now to some related literature.

Our model points to the interaction between learning and investment. As is well understood, for static problems it does not matter whether agents know the probability of an accident, or whether they merely have a distribution of probabilities. When the problem of prevention is repeated over time, however, learning and care-taking interact in non-trivial ways. Gollier (2002) has studied how the curvature (and higher derivatives) of the utility function of the decision maker affect the optimal initial level of care taken when the probability of the accident is unknown. In contrast, our main concern is the study of the evolution of beliefs and how this evolution affects investment over time.

One of the main features of our model, that strings of successes lead to lower care, is reminiscent of the search literature when the distribution that generates wage offers is unknown. This literature has shown that as time goes by, a worker who keeps receiving bad offers becomes more pessimistic about his prospects of finding a decent paying job. He then reduces his reservation wage. The first papers to analyze the decline in reservation wages were, under different assumptions, Rothschild (1974) and Burdett and Vishwanath (1984). Dubra (2004) studies the consequences of this decline on the welfare of the decision-maker.

2 Complex Systems

A lifeguard must continually scan a pool, or a beach, for signs of swimmers in distress. Unfortunately, even highly trained lifeguards may fail to maintain the necessary vigilance.[14] The model of Section 1 suggests that lifeguards who face few emergencies will be especially prone to lapses in vigilance. This finding is consistent with experimental work in psychology which shows that subjects engaged in vigilance tasks perform relatively poorly when the signal rate is low.[15]

While the meandering mind of a lifeguard may prove lethal, the danger posed pales in comparison to the potential harm from a nuclear or chemical plant. For this reason, these plants are designed so that the complacency of a single individual is not sufficient for a disaster to ensue. Consider the following description of an incident at a Union Carbide plant in Institute, West Virginia (Perrow (1999)):

> "[Dangerous] Aldicarb oxime... was transferred to a standby tank that was being pressed into service because of some other problems. Unfortunately, the operators did not know that this tank had a heating blanket and that it was set to come on as soon as it received product. Also unfortunately, they were not examining

[14] A 2001 Jeff Ellis & Associates study conducted at 500 swimming pools found that only 9% of lifeguards spotted a submerged mannequin within 10 seconds (considered crucial), and only 43% within 30 seconds.

[15] These vigilance tasks typically last no more than two hours, so that these experiments are not, of course, full blown tests of our theory. See Davies and Parasuraman (1981) for a survey.

the appropriate temperature gauges because they thought there was no need to, and there may have been problems with these anyway because of the nature of the product in the tank. A couple of warning systems failed to activate, and the tank blew... . A few other failures took place..." (p. 358)

Note the number of elements that fell into place to produce this accident: a standby tank was being used *and* there was a heating blanket *and* it was set to come on *and* the operators did not check the temperature gauges *and* warning systems failed *and* the tank blew *and* ... still other things happened. Even with all these failures, there was no loss of life, partly because weather conditions were propitious.

Certainly, the large number of factors that must align in order to produce an accident at a chemical plant contributes to its safety.[16] More generally, consider a system with numerous safety features, all of which must fail for a disaster to result. If the features might fail with given independent probabilities, then the more features, the safer the system. With fully automated features, the logic is unassailable. If humans are involved, however, features that are ostensibly independent may manifest a "strategic dependence," resulting in an ambiguous relationship between reliability and the number of features.

Returning to the Union Carbide case described above, the mere failure of the operators to check the temperature gauges was a long way from producing an accident. But why did the operators fail to check the gauges?[17] The immediate reason given is that "they thought there was no need to," but why did they feel no need to follow such an elementary safety precaution? In this section we suggest that at least part of the reason was that the operators knew that even with this lapse, an accident was unlikely, precisely because so many factors had to go awry in order to produce one. That is, the very redundancy features which enhanced the safety of the plant also reduced the incentive of agents to take care, thus limiting the degree of safety that could be achieved.

We turn now to a formal model of this phenomenon.

A disaster may occur. The disaster will happen if and only if each of $n+1$ features fail – an automated feature plus n features under the control of n different people. The probability that the automated feature fails is p_a, while the probability that person i's feature fails is $p(c_i)$, $i = 1, ..., n$, where $c_i \in S = [0, M]$ is the care that i puts in, $p'(c) < 0$, and $p''(c) \geq 0$. Person i's utility function is

$$-p_a \pi_{j=1}^{n} p(c_j) D - c_i,$$

where $D > 0$ reflects the loss of utility from a disaster.[18]

[16] Perrow (1999), however, emphasizes the *dynamic* danger of tightly coupled complex systems, such as chemical plants. When things start to go wrong in these systems, it is difficult for workers to understand exactly where the problem lies and how to remedy it on the fly. Thus, whereas we will take a static view in our modelling, Perrow is concerned with dynamic difficulties. Nonetheless, Perrow concedes that the number of failures that must take place for an accident to occur, per se, provides a crucial measure of safety.

[17] Similar lapses in care have been noted at numeous other accident sites, including Three Mile Island.

[18] Note that, viewed as a principal-agent problem, we are assuming that the agents fully internalize the cost of a disaster, as in the belief-agency problem of Section 1. Under an alternate interpretation, the principal has chosen a payment function with large rewards for agents when no disaster occurs. Macdonald and Marx (2001) give (unrelated) reasons why a principal might choose such a payment function.

If each person were an automaton simply putting in a designated amount of effort $\bar{c}$, then the probability of a disaster would be $p_a p(\bar{c})^n$. Trivially then, increasing the number n of manned features would reduce the probability of an accident, as would better automation in the form of a lower p_a.

Of course, people are not automata; rather, they choose their efforts purposefully. This fact has several consequences. Consider the game in which care levels are chosen simultaneously. Proposition 4 below indicates that as the number of people increases, each person takes less care in the unique symmetric equilibrium. Similarly, when the automatic feature improves, each person takes less care. An estimation of the safety of the system that neglects this strategic slackening will badly miss the mark.

While these reductions in individual care raise the probability of a disaster, increases in the number of people and improvements in automation, in and of themselves, lower this probability; the net effect is ambiguous. Importantly, under reasonable conditions, increasing the number of people or improving the automated performance may be counterproductive. The following proposition summarizes these findings.

Proposition 4 *The above game has a unique symmetric equilibrium. Let $C(p_a, n)$ be the level of care and $P(p_a, n)$ be the probability of an accident, in this equilibrium. Then,*

i) C is decreasing in n
ii) C is increasing in p_a
iii) P may be increasing or decreasing in its arguments.
In particular, suppose the equilibrium is interior
(i.e., $-p(0)^{n-1} p'(0) > \frac{1}{Dp_a} > -p(M)^{n-1} p'(M)$), and consider $n' > n$ and $p'_a > p_a$.
If $\frac{p}{p'}$ is strictly increasing, then $P(p_a, n') > P(p_a, n)$ and $P(p'_a, n) < P(p_a, n)$;
if $\frac{p}{p'}$ is strictly decreasing, then $P(p_a, n') < P(p_a, n)$ and $P(p'_a, n) > P(p_a, n)$.

Psychologists have long noted that people working in groups tend to expend less effort than people working as individuals, with larger groups exhibiting more "social loafing."[19] This finding corresponds to i) above. They have also observed that the introduction of automatic devices leads to a decrease in human performance, which corresponds to ii) above.[20] Skitka et al. (2000) put subjects in simulated cockpits with imperfect automated monitoring aids. They then compared the performance of one-person crews with the performance of two-person crews. Although one might naively expect two-person crews to be almost twice as likely to detect system irregularities as one-person crews, they found essentially no difference in detection rates, which is consistent with iii) (albeit in a relatively neutral way).

The following examples illustrate some interesting features of Proposition 4. In the first example, the optimal number of care-takers is an intermediate value.

[19] Pschologists' explanations for social loafing include arousal reduction, decreased evaluation potential, and a matching of anticipated decreased effort on the part of others (see Karau and Williams (1993) for a review).

[20] Psychologists' explanations include automation bias, and automation induced complacency. Consistent with ii), Skitka et. al (1993) find that experimental subjects are less reliable at detecting errors when aided by an automatic system. On the other hand, Parasuraman et al. (1993) conduct an experiment in which they find that the variability in the reliability of an automated system, but not the absolute value of this reliability, affect performance, a finding which is not consitent with ii) (although the interpretation of this finding is confounded by the fact that subjects were not given the reliability parameters).

Example 1 $S = [0,1]\,, p_a D = 40, p(c) = 1-\frac{5}{4}c+\frac{1}{2}c^2$. *For any* n*, the symmetric equilibrium* c_n *solves* $-p_s D\left(1-\frac{5}{4}c_n+\frac{1}{2}c_n^2\right)^{n-1}\left(c_n-\frac{5}{4}\right)=1$. *The accident minimizing number of people is given by*

$$\arg\min_n P(p_a, n) = 5$$

In the second example, technological considerations restrict p_a to the interval $\left[\frac{1}{2},1\right]$. The probability of an accident $P(p_a,n)$ is minimized by choosing the least reliable automation within this set.

Example 2 $S = [0,1]\,, D > 2, p(c) = (1-c)^b\,,\ 1 \leq b < \frac{n+1}{n},\ p_a \in \left[\frac{1}{2},1\right]$. *For any* p_a*, the symmetric equilibrium is* $c = 1-(bDp_s)^{\frac{1}{1-bn}}$.

$$\arg\min_{p_a\in\left[\frac{1}{2},1\right]} P(p_a, n) = 1$$

Example 3 *Our model is formally a generalization of the Volunteer's Dilemma (Samuelson (1984) and Diekmann (1985)). In this dilemma, an event can be prevented if and only if at least one of* n *people takes a costly action. Each individual's payoff is given by:*

	Someone Else Acts	*No One Else Acts*
Takes Action	-1	-1
No Action	0	$-D$

In the symmetric mixed strategy equilibrium of this game, the probability of an event is monotonically increasing in n*. This result can be viewed as a special case of Example 2. To see this, set* $b = 1, p_a = 1$*. Then, a mixed strategy* $(q, 1-q)$ *in the Volunteer's Dilemma corresponds to a pure strategy* $c = q$ *in Example 2. Since the equilibrium is interior, and* $\frac{p}{p'} = c-1$ *is an increasing function, (iii) yields the Dilemma result that* P *is increasing in* n*. Since Darley and Latané (1968) introduced the concept of "diffusion of responsibility" into the psychology literature, this type of prediction has been tested often, with varying results (see Goeree, Holt and Moore (2005) and the references therein).*

Our results are also reminiscent of the "voluntary provision of public goods" literature. It has long been known that the provision of public goods is subject to a free rider problem, and since Olson (1965) it has been argued that the severity of the problem increases with the number of individuals in society. Since then, several authors have produced examples where the ratio between the optimal amount of a public good and the equilibrium amount of a voluntary provision game increases with the number of players. The only result giving general sufficient conditions for this effect is in Gaube (2001). As in Gaube, we give sufficient conditions for the problem of underprovision to be exacerbated as n increases, but in addition we give sufficient conditions for the converse result to hold: we provide sufficient conditions under which the amount of the public good provided is increasing in n. In several other respects, our model is not comparable to this literature. In particular, in voluntary provision models, the public good is generally assumed to be the sum of the contributions c_i, whereas in our model it is $(1 - p_a \pi_{i=1}^{n} p(c_i))$, and the benchmarks used to evaluate the problems are different.[21]

For a complex system requiring supervision, we may expect that, on the one hand, even a supervisor putting in a minimal amount of effort might detect an anomaly, while on the other hand, even a supervisor putting in a maximal amount might miss an anomaly. Formally, this translates to $0 < p(M) < p(0) < 1$. Since $p(0) < 1$, the accident-minimizing number of people is then infinity. In practice, however, the "optimal" number of people will be less than infinity, for both technological reasons and economic reasons. As this section emphasizes, there may well be a non-monotonic relationship between the number of people and the probability of an accident, so that the optimal number of people is not necessarily the "constrained largest." At the same time, since $p(M) > 0$, the optimal number of people is unlikely to be one, in contrast with the Volunteer's Dilemma.

3 Elected Officials

As of this writing, governments throughout the world face the question of how best to deal with the menace of Aviary flu. While experts weigh in with divergent opinions on the danger posed, and by implication the appropriate government action, there is an additional aspect to the problem. In deciding how much to invest in precautionary care, elected officials subject to reelection must consider how their actions will be interpreted by the electorate. In this section, we show that this added concern may cause them to misinvest, even when they have a very good understanding of the threats facing the public. In particular, officials have an incentive to underinvest in prevention for potential disasters with relatively low probabilities of occurrence.

Consider the following model. In any period an adverse event may occur with probability p_i, where $i = l$ or h, and $0 \leq p_l < p_h \leq 1$. The prior probability that $p_i = p_h$ is p. An incumbent official, who may or may not be competent, must invest in preventive care. The official has been elected from a pool of (qualified) candidates, and the electorate initially believes that he, as well as any future candidate, is competent with probability $0 < q < 1$. At the same time, an official believes that he himself is competent with probability $0 < Q \leq 1$. These probabilities are assumed to be common knowledge. Note that if $q \neq Q$ the beliefs of the official and the public are inconsistent;[22] this causes no modeling problems and, when $Q > q$ captures the oft-seen case of officials confident in their own abilities. Whether competent or incompetent, the official receives a private signal $s \in \{h, l\}$. If he is competent, then $s = i$; otherwise $s = h$ with probability p. With this signalling structure, an official's signal is uninformative about his own competence, and an incompetent official's signal is

[21] Cornes (1993) analyzes the case in which the public good is produced via a Constant Elasticity of Substitution production function in which inputs are individual contributions. This case covers the standard case, plus other interesting cases. He does not analyze, however, the effect of increasing the number of individuals.

[22] An alternate "consistent" model would have the officials receive private signals regarding their competence, starting from a common prior. Similar results would obtain. We prefer the model in the text for several reasons, one of which is that it obviates the need for mixed strategies. The reader who prefers consistent models can restrict his or her attention to the case $q = Q$.

uninformative about the true probability of a disaster.[23]

An official is initially elected for τ periods and may be re-elected exactly once. Each period, he chooses a level of care. The optimal level of care in period t depends upon a priori information, whether or not there have been disasters in periods before t, and the official's signal s. The only piece of information that is private is the official's signal, and so we can simplify by boiling the official's action down to a declaration of his signal. A strategy for the official is a function $\sigma : \{h, l\} \to [0, 1]$, which maps his signal into a probability with which he announces that h was observed.

In each period, in addition to investment into disaster preparation, the official makes numerous invisible decisions which are more likely to be correct if the official is competent than incompetent. The public wants competent officials in place, and rationally updates its belief about an incumbent official based upon his strategy, his declaration, and the realized pattern of disasters during his initial τ year term. A newly elected official will be competent with probability q. Therefore, the public will re-elect a first term official if its belief that he is competent is greater than q, and will not re-elect him if its belief is less than q. If its belief is exactly q, the official is re-elected with a 50% probability. The official cares only about being re-elected (this extreme assumption highlights the problems that arise). Therefore, the official chooses his declaration to increase the probability that the public's faith in him will increase.[24]

The efficient outcome is for the official to always truthfully report his signal (and make the concomitant investment in care). Unfortunately, under many conditions this will not be equilibrium behavior.

Suppose that the official is certain that he is competent (i.e., $Q = 1$), and hence is certain that his signal correctly reflects the true probability of a disaster (i.e., $\Pr(p_i = p_s \mid s) = 1$). As intuition suggests, this condition maximizes the official's incentive to tell the truth (see Proposition 8 below). Indeed, if his term were arbitrarily long, he would then truthfully reveal any signal, since, by the law of large numbers, the realization of disasters during his term would then almost surely conform to his signal,[25] and the public's confidence in his competence would increase. The official's term is not arbitrarily long, however. Suppose that this term is, on the contrary, relatively short and that the probability of a disaster is, at worst, quite small (i.e., $p_h << 1$). Then, *regardless* of his signal, the official ascribes less than a 50% chance to the occurrence of even one event during his initial term. If no event occurs, the public's posterior belief that $p_i = p_h$ will fall (albeit slightly). Suppose the official receives the signal h. He will not want to reveal this signal, since future happenings will more than likely reduce the electorate's belief that $p_i = p_h$, contravening the signal h, and reducing the electorate's belief in his competence if his signal is public. Thus, under these conditions, there is no efficient equilibrium.

[23] That is, $p(\text{competent} \mid s) = \frac{\Pr(s|c)\Pr(c)}{\Pr(s|c)\Pr(c)+\Pr(s|i)\Pr(i)} = Q$, and for an incompetent official $p(p_i = p_h \mid s) = p$.

[24] In a more complex model, the official also makes other public decisions that influence the public's perception of him. If these decisions do not have much influence, our results are unaffected, although the model becomes more cumbersome. If these other decisions can have a large impact on the public's beliefs, then the effects we identify are still present, but may be counterbalanced in some instances.

[25] More precisely, the official would believe that the realizations would conform to his signal, and this belief is all that matters.

What are the conditions for the existence of an efficient equilibrium? Again consider an official who receives the signal h. He is willing to reveal this signal if he expects this revelation to increase the electorate's confidence in him, that is to say, if he believes that subsequent developments are likely to be indicative of p_h. The greater the number of events N_E that occur during his term, the more likely that $p_i = p_h$. There is a threshold f so that the belief that $p_i = p_h$ will increase if and only if the average number of events, $\frac{N_E}{\tau}$, is above this threshold. The official will reveal h if $\Pr\left(\frac{N_E}{\tau} \geq f \mid h\right) \geq \frac{1}{2}$, where

$$\begin{aligned} & \Pr\left(\frac{N_E}{\tau} \geq f \mid h\right) \\ = \; & \Pr\left(p_i = p_h \mid h\right) \Pr\left(\frac{N_E}{\tau} \geq f \mid p_h\right) + \Pr\left(p_i = p_l \mid h\right) \Pr\left(\frac{N_E}{\tau} \geq f \mid p_l\right) \end{aligned}$$

Similar reasoning applies to the revelation of the signal l, as the Proposition 5 below shows.

Recall that an official's strategy σ gives the probability with which he declares "h". An equilibrium is **efficient** if $\sigma(l) \in \{0,1\}$ and $\sigma(l) = 1 - \sigma(h)$. An equilibrium is **babbling** if $\sigma(l) = \sigma(h)$.

Proposition 5 *Fix any generic p_l and p_h, and any p, q, Q and τ. A babbling equilibrium always exists. All equilibria are babbling if*

$$\Pr\left(p_i = p_h \mid h\right) \Pr\left(\frac{N_E}{\tau} \geq f \mid p_h\right) + \Pr\left(p_i = p_l \mid h\right) \Pr\left(\frac{N_E}{\tau} \geq f \mid p_l\right) < \frac{1}{2} \quad (1)$$

$$\text{or} \quad \Pr\left(p_i = p_h \mid l\right) \Pr\left(\frac{N_E}{\tau} \leq f \mid p_h\right) + \Pr\left(p_i = p_l \mid l\right) \Pr\left(\frac{N_E}{\tau} \leq f \mid p_l\right) < \frac{1}{2} \quad (2)$$

where

$$f = \frac{\log\left(\frac{1-p_h}{1-p_l}\right)}{\log\left(\frac{p_l}{p_h}\right) + \log\left(\frac{1-p_h}{1-p_l}\right)}.$$

If both the above inequalities are violated there are efficient equilibria, and if they are violated strictly there are only efficient and babbling equilibria.

Proposition 5 is a bit technical, but it serves as the basis for the remaining, more applied, propositions. The next result indicates that all equilibria are babbling when only relatively small probability events or only relatively large probability events are involved.

Proposition 6 *Fix $Q \leq 1$ and $\tau \geq 1$. For low enough p_h, all equilibria are babbling; for large enough p_l, all equilibria are babbling.*

When terms are long, efficient equilibria exist if and only if the signals are reliable enough.[26]

[26] When τ is very large, it is *as if* the true state of the world is revealed. In this respect, our model is a generalization of Ottaviani and Prat (2006). However, they have a continuous signaling structure so in that respect, their model is a generalization of ours for τ large.

Proposition 7 *Fix any generic p_l and p_h and any p, q, Q. There exists a $\bar{\tau}$ such that for all $\tau > \bar{\tau}$, an efficient equilibrium exists only if* $\Pr(p_i = p_h \mid h) \geq 1/2 \geq \Pr(p_i = p_h \mid l)$. *If in addition the inequalities are strict, there is a $\bar{\tau}$ such that for all $\tau > \bar{\tau}$ the only non-babbling equilibria are efficient.*

The more confident the official, the more likely that an efficient equilibrium exists.

Proposition 8 *Suppose that for a given p_l, p_h, p, q, Q, τ there is an efficient equilibrium. Then, for all $Q' > Q$ there is also an efficient equilibrium for p_l, p_h, p, q, Q', τ.*

The menace posed by Aviary flu is best viewed as a potentiality which will or will not be realized once, rather than an event which may or may not occur in successive periods with i.i.d probabilities. We can capture this in our model by setting the official's term τ to 1. Then, p_i is the probability of an outbreak during the official's initial term. The following result says that there is then no efficient equilibrium when the probability of an outbreak is always less than $\frac{1}{2}$, or always greater than $\frac{1}{2}$.

Proposition 9 *When $\tau = 1$, all equilibria are babbling if $p_h < \frac{1}{2}$ or $p_l > \frac{1}{2}$.*

The formal modelling heretofore describes an electorate that understands equilibrium behaviour perfectly. In a plausible alternative the electorate (naively) interprets the official's declaration. Moreover, while our officials make explicit announcements of their signals, in practice governments often implicitly indicate their beliefs by their investments. The following proposition indicates that under these conditions, inadequate preventative care will be taken for small probability disasters.

Proposition 10 *Suppose the public (naively) assumes that the official always invests optimally in relation to his signal. Then, if p_h is small enough the official underinvests when he receives the signal h. In particular, if $\tau = 1$ and $p_h < \frac{1}{2}$ then, regardless of his signal, the official invests as if he received the signal l.*

Suppose that $\tau = 1$, $q_L = 0$, $q_h < \frac{1}{2}$, and $Q \approx 1$. Then the official's incentive is to not invest in any preventive care, *regardless* of the potential damage D. While this conclusion may seem extreme, it provides a plausible account for much government behaviour. For example, consider preparations for a hurricane. The (average member of the) public is likely to take direct note of these preparations only if a hurricane strikes. Absent a hurricane, the expenditure incurred is indirectly noted in that greater expenditure leaves less money over for other items. It was well-recognized before the Category 5 hurricane Katrina struck, that the levees in New Orleans would be inadequate to withstand a strong hurricane. Furthermore, most experts believed that the chance of such a hurricane was high enough to warrant investing in better levees. Indeed, a review by the Army Corps of Engineers later found that the Corps had 'designed the system to protect New Orleans against a relatively low-strength hurricane... and did not respond to warnings over the years from the National Oceanographic and Atmospheric Administration that a stronger hurricane should have been the standard.' (as reported in the New York Times (2006)). At the same time, however, the historical record showed that the probability of a Category 5 hurricane was only 2.4% during a four year period and 4.7% during an 8 year period.[27] Thus, the government's failure to prepare adequately can be understood as a rational bet that developments would increase the public's confidence in it, inadequate preparations notwithstanding. At the same time, given the magnitude of the potential (and actual) damage, the bet was a poor one from an expected value perspective.[28]

For some potential disasters there will be efficient equilibria, for others only babbling equilibria. When there are only babbling equilibria, the public could be better off committing to re-electing officials, regardless of their perceived competence, since officials would then have no incentive to hide their signals. With the right discount rates, these commitments could arise as part of an equilibrium.[29] However, these equilibria disappear if we assume that officials must pay even a small cost to obtain their signals, as they have no incentive to acquire signals if guaranteed re-election.

The model in this section investigates inefficiencies that arise from the interaction between disaster prevention and career concerns on the part of elected officials. In the seminal Holmstrom (1982, reprinted 1999), a manager whose talent is being judged, fails to optimize over project choice, either because he is risk averse or because a "lemons-type" problem arises, neither of which is the case here. Another difference with our model, is that the talents of Holmstrom's managers affect the relevant probabilities, whereas our officials only evaluate probabilities. Scharfstein and Stein (1990) study the inefficiency that arises when managers observe the same signals about the likelihood of success of projects. In their model, managers tend to herd on the choice of projects, so that the market will not be able to update on their ability. The model is similar to ours in that the skill of the official-manager is at evaluating the likelihood of success, and that they also consider a career concerns model. The mechanism whereby the inefficiency arises is different, however. Ottaviani and Sorensen (2004) consider a model in which experts only care about their reputation for competence, and find that they will not truthfully reveal their signals. In their model, the true state of the world is eventually known, whereas in our setting only an update of the state obtains. For this reason, prior probabilities play a much stronger role in their model than ours. Dasgupta and Prat (2004) show that financial traders with reputational concerns may ignore their private information, leading to information cascades.[30]

[27] The return period for Category 5 hurricanes in the New Orleans area is 165, meaning to say that they return, on average, every 165 years, or that 100/165 have occurred in the last 100 years. If this is the result of independent Bernoulli trials, the most likely probability of a hurricane in a given year is approximately 3/500, and the chances that no hurricane will occur in 4 and 8 year periods are the figures given in the text.

[28] Damage that may occur in the future, such as the potential harm from global warming or decaying infrastructure, may lead governments to underinvest due to a lack of concern for future generations, or an inappropriate discount rate. This should not be confused with the present phenomenon; here, the current population is suffering (in expectation).

[29] Thus efficency could be obtained with respect to the officials' strategies, but not also with respect to only re-electing relatively competent officials.

[30] Other models of career concerns include Celentani and Caruana (2001), where managers get to know their types, and Dewatriapont, Jewitt and Tirole (1999) where effort has a cost.

4 Conclusion

Though an ounce of prevention may be worth a pound of cure, that ounce is often missing. Inadequate care can be the result of miscalculations and other errors. Thus, many analyses of the Challenger disaster have emphasized the increasing pressure to launch brought about by the commercialization of the Space Shuttle. We have shown that imprevention can also be the result of a rational calculus.

5 Appendix

For the proof of Proposition 1, we proceed with a series of simple Lemmas concerning the evolution of beliefs. Although versions of the following lemma are well known (see Wolfstetter (1999) Chapter 4) we will use the strict inequalities in this version of our Lemma.

Lemma 1 *If two densities p' and p are such that p'/p is strictly increasing on their support $[0,1]$, then, for all $x \in (0,1)$, their cumulative distribution functions are such that $P'(x) < P(x)$.*

Proof. Let $\overline{x}$ be such that $p'(\overline{x}) = p(\overline{x})$. Then, for all $x \in (0, \overline{x})$ we have $p'(x) < p(x)$ and so $P'(x) < P(x)$. For $x > \overline{x}$, $P'(x) - P(x)$ is increasing in x, since the derivative is strictly positive, and therefore is strictly less than $P'(1) - P(1) = 0$. ■

Lemma 2 *For all densities p with support $[0,1]$, the posterior p_n of p is such that $P_n(\theta \leq x) > P(\theta \leq x)$.*

Proof. By Bayes' Rule, the density of the posterior P_n is

$$p_n(\theta) = \frac{\Pr(n \mid \theta) \Pr(\theta)}{\Pr(n)} = \frac{(1-\theta)\, p(\theta)}{\int_0^1 (1-z)\, p(z)\, dz}$$

so that the likelihood ratio of p and p_n is

$$\frac{p(\theta)}{p_n(\theta)} = \frac{\int_0^1 z p(z)\, dz}{1-\theta}$$

which is strictly increasing in θ, so that by Lemma 0, $P_n(\theta \leq x) > P(\theta \leq x)$. ■

Proof of Proposition 1. Since θ is a strictly increasing function, and, by Lemma 2, p strictly dominates $p \mid n$, the result follows. ■

Proof of Proposition 2. To establish uniqueness, fix any p. Suppose that c' and c are optimal for p, with $c' > c \geq 0$. Given our assumptions about differentiability, c' must satisfy the first order condition $-\phi_2(\widehat{p}, c')\, D = 1$, but then $\phi_{22} > 0$ implies that $-\phi_2(\widehat{p}, c)\, D > 1$, so that c can't also be optimal.

If $c(\widehat{p}_n) = 0$ we are done, so suppose that $c(\widehat{p}_n) > 0$. From the first order conditions, $-\phi_2(\widehat{p}, c(\widehat{p}))D = 1 = -\phi_2(\widehat{p}_n, c(\widehat{p}_n))D$. Since $\widehat{p}_n < \widehat{p}$, $\phi_{12} < 0$, and $\phi_{22} > 0$, we have that $c(\widehat{p}_n) < c(\widehat{p})$. ■

Proof of Proposition 3. We first show that for all $t > T^*$ we have $\widehat{q}_{n^t} < \widehat{p}_{n^t}$. Notice that after t draws of n, the posteriors of the agent and the principal are $B(a+t, b)$ and $B(d+t, e)$ respectively. Then, $\widehat{q}_{n^t}$ and $\widehat{p}_{n^t}$ are just the means of the posteriors, and hence

$$\widehat{q}_{n^t} < \widehat{p}_{n^t} \Leftrightarrow \frac{b}{a+b+t} < \frac{e}{d+e+t} \Leftrightarrow t > \frac{bd-ae}{e-b}.$$

Fix any $t > T^*$. If $c(\widehat{q}_{n^t}) = 0$ we are done, so suppose that $c(\widehat{q}_{n^t}) > 0$. From the first order conditions, $-\phi_2(\widehat{p}_{n^t}, c(\widehat{p}_{n^t}))D = 1 = -\phi_2(\widehat{q}_{n^t}, c(\widehat{q}_{n^t}))D$. Since $\widehat{q}_{n^t} < \widehat{p}_{n^t}$, $\phi_{12} < 0$, and $\phi_{22} > 0$, we have that $c(\widehat{q}_{n^t}) < c(\widehat{p}_{n^t})$. ■

Proof of Proposition 4. First note that the players' strategy spaces are compact and convex, their utility functions are continuous and concave, and the game is symmetric, so the game has at least one symmetric equilibrium. We now show that there is exactly one symmetric equilibrium.

Suppose that $c = 0$ is a symmetric equilibrium. Then

$$-p_a p(0)^{n-1} p'(0) D - 1 \le 0$$

We have

$$\begin{aligned} \frac{d}{dx}\left(-p_a p(x)^{n-1} p'(x) D - 1\right) &= \\ -p_a(n-1) p(x)^{n-2} p'(x) p'(x) D - p_a p(x)^{n-1} p''(x) D &< 0, \end{aligned} \tag{3}$$

so that

$$-p_a p(x)^{n-1} p'(x) D - 1 < 0 \ \forall x \neq 0$$

and there can be no other symmetric equilibrium. Similarly if $c = M$, there are no other symmetric equilibria. Therefore, if there is a corner symmetric equilibrium, it is the unique symmetric equilibrium.

If $c = \underline{c}$ is an interior symmetric equilibrium then

$$-p_a p(\underline{c})^{n-1} p'(\underline{c}) D = 1,$$

and, since inequality (3) still holds, there is no other interior symmetric equilibrium.

Proof of i) Suppose that $N > n$. If $C(p_a, n) := c$ is interior, then $-p_a p(c)^{n-1} p'(c) D = 1$. Therefore, $-p_a p(c)^{N-1} p'(c) D < 1$, and inequality (3) implies that $C(p_a, N) < C(p_a, n)$. If $C(p_a, n) = 0$, then $-p_a p(0)^{n-1} p'(0) D \le 1$ and $-p_a p(0)^{N-1} p'(0) D < 1$, so that $C(p_a, N) = 0$. Finally, if $C(p_a, n) = M$, then necessarily $C(p_a, N) \le C(p_a, n)$.

Proof of ii). Suppose that $q_a > p_a$. If $C(p_a, n) := c$ is interior, then $-p_a p(c)^{n-1} p'(c) D = 1$. We have, $-q_a p(c)^{N-1} p'(c) D > 1$, and inequality (3) implies that $C(q_a, n) > C(p_a, n)$. If $C(p_a, n) = M$, then $-p_a p(0)^{n-1} p'(0) D \ge 1$ and $-q_a p(0)^{N-1} p'(0) D > 1$, so that $C(q_a, n) = 0$. Finally, if $C(p_a, n) = 0$, then necessarily $C(q_a, n) \ge C(p_a, n)$.

Proof of iii). Suppose $-p(0)^{n-1} p'(0) > \frac{1}{Dp_a} > -p(M)^{n-1} p'(M)$ holds. Then, the first order condition at $c = 0$ (when all are playing 0) is

$$-p_a p(0)^{n-1} p'(0) D - 1 > 0$$

so that 0 is not a symmetric equilibrium. Similarly, at M, the first order condition is $-p_a p^{n-1}(M)\,p'(M)\,D - 1 < 0$, so that $c = M$ for all players is not an equilibrim.

Fix any $n' > n$ and let $C(p_a, n) := c$ and $C(p_a, n') := c'$. We now show that $P(p_a, n') > P(p_a, n)$ whenever p/p' is strictly increasing. From the proof of i), $c' < c$. Since c is interior, $p(\cdot)/p'(\cdot)$ strictly increasing implies

$$P(p_a, n) = -\frac{p(c)}{Dp'(c)} < -\frac{p(c')}{Dp'(c')} \leq P(p_a, n').$$

The proof for $\frac{p(c')}{p'(c')} > \frac{p(c)}{p'(c)}$ follows similarly.

Now suppose that $p_a' > p_a$ and let $c' > c$ be the corresponding equilibrium efforts. An identical argument establishes the desideratum. ■

We now turn to the proofs of the Propositions in Section 3

An event E is a sequence $\{d_s\}_1^\tau$ for $d_s \in \{y, n\}$ for all s; let N_E be the number of disasters in event E. For each fixed τ, and p_x, $x = h, l$, the probability of E given p_x is

$$\Pr(E \mid p_x) = p_x^{N_E}(1 - p_x)^{\tau - N_E} \tag{4}$$

so that

$$\frac{\Pr(E \mid p_h)}{\Pr(E \mid p_l)} = \left(\frac{p_h}{p_l}\right)^{N_E}\left(\frac{1 - p_h}{1 - p_l}\right)^{\tau - N_E}.$$

Then, for (Lebesgue) almost every combination of p_h and p_l, the ratio above is different from 1 for *all* E (all $N_E \leq \tau$). Let $S_\tau \subseteq [0,1]^2$ be the set of p_h and p_l such that $\Pr(E \mid p_h)/\Pr(E \mid p_l) \neq 1$ for all E. The genericity in the statement of the propositions in this section refers to all p_h and p_l in S_τ.

From equation (4) we know that

$$\frac{\Pr(E \mid p_l)}{\Pr(E \mid p_h)} \leq 1 \Leftrightarrow N_E \geq \tau\frac{\log\left(\frac{1-p_h}{1-p_l}\right)}{\log\left(\frac{p_l}{p_h}\right) + \log\left(\frac{1-p_h}{1-p_l}\right)} \equiv \tau f(p_h, p_l). \tag{5}$$

Then, since for all E, $\Pr(E \mid p_l) \neq \Pr(E \mid p_h)$ (that is, $(p_h, p_l) \in S_\tau$) we have that

$$\Pr(N_E \geq \tau f(p_h, p_l) \mid p_h) = 1 - \Pr(N_E \leq \tau f(p_h, p_l) \mid p_h) \tag{6}$$

and similarly,

$$\Pr(N_E \geq \tau f(p_h, p_l) \mid p_l) = 1 - \Pr(N_E \leq \tau f(p_h, p_l) \mid p_l) \tag{7}$$

Proof of Proposition 5. Existence of Babbling Equilibria. If the public believes that $\sigma(l) = \sigma(h) = x$, then it will not update for any announcement or event E,and $\sigma(l) = \sigma(h) = x$ is a best response. This holds for any parameters

All non babbling equilibria are efficient, when (1) and (2) are violated strictly. Fix any proposed equilibrium strategy with $\sigma(l) \neq \sigma(h)$. The public's strategy, given $\sigma(l)$ and $\sigma(h)$ is to rehire if the probability of the individual being competent given the strategies, the announcement $a = h, l$ and the event E,is larger than q. The probability of the individual being competent given $a = h$ is

$$\begin{aligned} P(c \mid \sigma, a = h, E) &= \frac{P(a = h, E \mid c, \sigma) q}{P(h, E \mid c, \sigma) q + P(h, E \mid i, \sigma)(1-q)} \\ &= \frac{1}{1 + \frac{\left[(p\sigma(h)+\sigma(l)(1-p))\frac{P(E|p_h)}{P(E|p_l)}\frac{p}{1-p}+p\sigma(h)+\sigma(l)(1-p)\right](1-q)}{\left[\sigma(h)\frac{P(E|p_h)}{P(E|p_l)}\frac{p}{1-p}+\sigma(l)\right]q}} \end{aligned}$$

This is greater than q iff

$$\begin{aligned} \frac{(p\sigma(h)+\sigma(l)(1-p))\frac{P(E|p_h)}{P(E|p_l)}\frac{p}{1-p}+p\sigma(h)+\sigma(l)(1-p)}{\sigma(h)\frac{P(E|p_h)}{P(E|p_l)}\frac{p}{1-p}+\sigma(l)} &\leq 1 \Leftrightarrow \\ (\sigma(h) - \sigma(l))\left[\frac{P(E \mid p_h)}{P(E \mid p_l)} - 1\right] &\geq 0. \end{aligned} \tag{8}$$

The probability of being competent if the individual announces $a = l$ is

$$P(c \mid \sigma, a = l, E) = \frac{1}{1 + \frac{\left[(p(1-\sigma(h))+(1-\sigma(l))(1-p))\frac{P(E|p_h)}{P(E|p_l)}\frac{p}{1-p}+p(1-\sigma(h))+(1-\sigma(l))(1-p)\right](1-q)}{\left[(1-\sigma(h))\frac{P(E|p_h)}{P(E|p_l)}\frac{p}{1-p}+1-\sigma(l)\right]q}}$$

which is greater than q iff

$$(\sigma(h) - \sigma(l))\left[\frac{P(E \mid p_h)}{P(E \mid p_l)} - 1\right] \leq 0 \tag{9}$$

Assume that $\sigma(h) > \sigma(l)$ (the opposite case is treated similarly). We will show that $\sigma(h) = 1$, by contradiction. Assume that 1 is strictly violated, and that $\sigma(h) < 1$. For $\sigma(h) < 1$ to be optimal it must be that, given the signal h, reporting l yields a utility weakly larger than reporting h. That is, from inequalities 9 and 8, it must be that

$$\begin{aligned} \Pr\left((\sigma(h) - \sigma(l))\left[\frac{P(E \mid p_h)}{P(E \mid p_l)} - 1\right] \leq 0 \mid h\right) &\geq \Pr\left((\sigma(h) - \sigma(l))\left[\frac{P(E \mid p_h)}{P(E \mid p_l)} - 1\right] \geq 0 \mid h\right) \Leftrightarrow \\ \Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \leq 1 \mid h\right) &\geq \Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \geq 1 \mid h\right) \end{aligned}$$

Since $(p_l, p_h) \in S_\tau$, (i.e. for generic p_h and p_l) $\Pr\left(\frac{P(E|p_h)}{P(E|p_l)} \leq 1 \mid h\right) = 1 - \Pr\left(\frac{P(E|p_h)}{P(E|p_l)} \geq 1 \mid h\right)$, the last inequality becomes

$$\begin{aligned} \frac{1}{2} &\geq \Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \geq 1 \mid h\right) \\ &= \Pr\left(\left(\frac{p_h}{p_l}\right)^{N_E}\left(\frac{1-p_h}{1-p_l}\right)^{\tau - N_E} \geq 1 \mid h\right) \\ &= \Pr(N_E \geq \tau f(p_h, p_l) \mid h) > \frac{1}{2} \text{ (since 1 is strictly violated),} \end{aligned}$$

A contradiction.

We now show that a contradiction obtains if we assume that 2 is strictly violated and $\sigma(l) > 0$. For $\sigma(l) > 0$ to be optimal, after observing l the utility of reporting h must be at least as large as the utility of reporting l. According to equations 9 and 8 this happens iff

$$\begin{aligned}
\Pr\left((\sigma(h)-\sigma(l))\left[\frac{P(E\mid p_h)}{P(E\mid p_l)}-1\right]\geq 0\mid l\right) &\geq \Pr\left((\sigma(h)-\sigma(l))\left[\frac{P(E\mid p_h)}{P(E\mid p_l)}-1\right]\leq 0\mid l\right)\Leftrightarrow\\
\frac{1}{2} &\geq \Pr\left(\frac{P(E\mid p_h)}{P(E\mid p_l)}\leq 1\mid l\right)\Leftrightarrow\\
\frac{1}{2} &\geq \Pr\left(\left(\frac{p_h}{p_l}\right)^{N_E}\left(\frac{1-p_h}{1-p_l}\right)^{\tau-N_E}\leq 1\mid l\right)\\
&= \Pr\left(N_E\leq \tau f(p_h,p_l)\mid l\right) > \frac{1}{2}(\text{1 strictly violated})
\end{aligned}$$

We conclude that $1 = \sigma(h)$ and $\sigma(l) = 0$, as was to be shown.

Existence of an efficient equilibrium if equations (1) and (2) are violated weakly. We now show that $1 = \sigma(h)$ and $\sigma(l) = 0$, is part of an equilibrium. We must establish two facts. First, having observed h, the official is better off declaring h than declaring l, assuming either declaration would be believed. This is true, according to the calculations following equations 9 and 8, iff

$$\begin{aligned}
\Pr\left(\frac{P(E\mid p_h)}{P(E\mid p_l)}\geq 1\mid h\right) &\geq \Pr\left(\frac{P(E\mid p_h)}{P(E\mid p_l)}\leq 1\mid h\right)\Leftrightarrow\\
\Pr\left(N_E\geq \tau f(p_h,p_l)\mid h\right) &\geq \frac{1}{2}
\end{aligned}$$

which holds since equation (1) is violated. Similarly, after observing l, announcing l is better than announcing h iff

$$\begin{aligned}
\Pr\left(\frac{P(E\mid p_h)}{P(E\mid p_l)}\leq 1\mid l\right) &\geq \Pr\left(\frac{P(E\mid p_h)}{P(E\mid p_l)}\geq 1\mid l\right)\Leftrightarrow\\
\Pr\left(N_E\leq \tau f(p_h,p_l)\mid l\right) &\geq \frac{1}{2}
\end{aligned}$$

which is satisfied because (2) is violated.

If equations (1) or (2) hold, the only equilibria are babbling. Suppose that $\Pr(N_E \geq \tau f(p_h, p_l) \mid h) < 1/2$ and that there is an equilibrium with $\sigma(h) > \sigma(l) \geq 0$. From equation 8 we know that $P(c \mid \sigma, a = h, E) \geq q$ iff

$$(\sigma(h)-\sigma(l))\left[\frac{P(E\mid p_h)}{P(E\mid p_l)}-1\right]\geq 0\Leftrightarrow \frac{P(E\mid p_h)}{P(E\mid p_l)}\geq 1$$

and that $P(c \mid \sigma, a = l, E) \geq q$ iff

$$(\sigma(h)-\sigma(l))\left[\frac{P(E\mid p_h)}{P(E\mid p_l)}-1\right]\leq 0\Leftrightarrow \frac{P(E\mid p_h)}{P(E\mid p_l)}\leq 1$$

If the proposed strategies are an equilibrium, then announcing h after observing h must be weakly better than announcing l, which happens iff

$$\begin{aligned}
\Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \geq 1 \mid h\right) &\geq \Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \leq 1 \mid h\right) \\
&= 1 - \Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \geq 1 \mid h\right) \Leftrightarrow \\
\Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \geq 1 \mid h\right) &\geq \frac{1}{2} \Leftrightarrow \Pr\left(N_E \geq \tau f(p_h, p_l) \mid h\right) \geq \frac{1}{2}
\end{aligned} \tag{10}$$

but the opposite is true, so $\sigma(h) > \sigma(l)$ cannot be an equilibrium.

Similarly, assume there is an equilibrium with $\sigma(h) < \sigma(l)$. In this case, $1 - \sigma(h) > 1 - \sigma(l) \geq 0$, which means that announcing l after observing h must be weakly better than announcing h, which happens iff

$$\begin{aligned}
\Pr\left((\sigma(h) - \sigma(l))\left[\frac{P(E \mid p_h)}{P(E \mid p_l)} - 1\right] \leq 0 \mid h\right) &\geq \Pr\left((\sigma(h) - \sigma(l))\left[\frac{P(E \mid p_h)}{P(E \mid p_l)} - 1\right] \geq 0 \mid h\right) \Leftrightarrow \\
\Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \geq 1 \mid h\right) &\geq \Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \leq 1 \mid h\right) \Leftrightarrow \\
\Pr\left(N_E \geq \tau f(p_h, p_l) \mid h\right) &= \Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \geq 1 \mid h\right) \geq \frac{1}{2}
\end{aligned}$$

which does not hold. The only alternative is $\sigma(h) = \sigma(l)$. ■

Proof of Proposition 6. Suppose there is a non babbling equilibrium, and assume without loss of generality that $\sigma(h) > \sigma(h)$. From the proof of Proposition 5, the part that shows that if equations (1) or (2) hold the only equilibria are babbling, we know that it must be the case that (see equation 10)

$$\begin{aligned}
\Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \geq 1 \mid h\right) &\geq \Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \leq 1 \mid h\right) \Rightarrow \\
\Pr\left(\frac{P(E \mid p_h)}{P(E \mid p_l)} \geq 1 \mid h\right) &\geq \Pr\left(E : N_E = 0 \mid h\right) \Leftrightarrow \\
\Pr\left(N_E \geq \tau f \mid h\right) &\geq \Pr\left(E : N_E = 0 \mid h\right)
\end{aligned} \tag{11}$$

Notice that for $p_h > p_l$ sufficiently close to 0

$$\Pr\left(N_E = 0 \mid p_h\right) = (1 - p_h)^{\tau} \text{ and } \Pr\left(N_E = 0 \mid p_l\right) = (1 - p_l)^{\tau}$$

are close to 1, and since $\tau f(p_h, p_l) > 0$, $\Pr(N_E \geq \tau f \mid p_h)$ and $\Pr(N_E \geq \tau f \mid p_l)$ become arbitrarily close to 0. Then, given $\Pr(N_E \geq \tau f \mid h) = \Pr(p_h \mid h)\Pr(N_E \geq \tau f \mid p_h) + \Pr(p_l \mid h)\Pr(N_E \geq \tau f \mid p_l)$ 0 and $\Pr(E : N_E = 0 \mid h) = \Pr(p_h \mid h)\Pr(N_E = 0 \mid p_h) + \Pr(p_l \mid h)\Pr(N_E = 0 \mid p_l) \simeq 1$, equation 11 becomes

$$0 \simeq \Pr\left(N_E \geq \tau f \mid h\right) \geq \Pr\left(E : N_E = 0 \mid h\right) \simeq 1,$$

a contradiction. ■

Proof of Proposition 7. Assume first that there is a $\bar{\tau}$ such that for all $\tau > \bar{\tau}$, an efficient equilibrium exists. Assume that contrary to what we want to prove $\Pr(p_i = p_h \mid h) < 1/2$ (the case of $\Pr(p_i = p_h \mid l) < 1/2$ is treated similarly). We will now show that condition 1 of Propostion 5 is satisfied (for large enough τ) so that no efficient equilibria exist. Rewrite condition 1 as

$$\begin{aligned}
\Pr(p_i = p_h \mid h)\Pr\left(\frac{N_E}{\tau} \geq f \mid p_h\right) + [1-\Pr(p_i = p_h \mid h)]\Pr\left(\frac{N_E}{\tau} \geq f \mid p_l\right) &< \frac{1}{2} \Leftrightarrow \\
\Pr\left(\frac{N_E}{\tau} \geq f \mid p_l\right) + \Pr(p_i = p_h \mid h)\left[\Pr\left(\frac{N_E}{\tau} \geq f \mid p_h\right) - \Pr\left(\frac{N_E}{\tau} \geq f \mid p_l\right)\right] &< \frac{1}{2}. \quad (12)
\end{aligned}$$

By the Law of Large numbers, and $p_h > f > p_l$, one can pick a large $\tau > \bar{\tau}$ and make $\Pr(N_E \geq \tau f \mid p_l)$ arbitrarily close to 0 and $\Pr(N_E \geq \tau f \mid p_h)$ arbitrarily close to 1, so that the left hand side in equation 12 is arbitrarily close to $\Pr(p_i = p_h \mid h)$. Since $\Pr(p_i = p_h \mid h) < 1/2$, equation 1 of Proposition 5 is satisfied and for such a τ, no efficient equilibrium exists.

Assume now that $\Pr(p_i = p_h \mid h) > 1/2 > \Pr(p_i = p_h \mid l)$ to show that all non-babbling equilibria are efficient. Again, by the Law of Large numbers, since $p_h > f$ for large enough τ $\Pr(N_E \geq \tau f(p_h, p_l) \mid p_h) \simeq 1$ and $\Pr(N_E \geq \tau f(p_h, p_l) \mid p_l) \simeq 0$, so that condition 1 of Proposition 5 is violated strictly. A similar argument applies to condition 2, using $f > p_l$. ■

Proof of Proposition 8. As Q increases from Q' to Q, we see that since

$$\begin{aligned}
\Pr(p_i = p_h \mid h) &= \frac{\Pr(h \mid p_h)\Pr(p_h)}{\Pr(h \mid p_h)\Pr(p_h) + \Pr(h \mid p_l)\Pr(p_l)} \quad (13)\\
&= \frac{(Q + p(1-Q))\,p}{(Q + p(1-Q))\,p + p(1-Q)(1-p)} = Q + p(1-Q) > p \\
\Pr(p_i = p_h \mid l) &= p(1-Q) < p \quad (14)
\end{aligned}$$

$\Pr(p_i = p_h \mid h)$ increases and and $\Pr(p_i = p_h \mid l)$ decreases. If an efficient equilibrium exists for Q', this means that both $\Pr(N_E \geq \tau f(p_h, p_l) \mid h) \geq 1/2$ and $\Pr(N_E \leq \tau f(p_h, p_l) \mid l) \geq 1/2$, in which case equations (1) and (2) tells us that inequalities are maintained for Q. ■

Proof of Proposition 9. Suppose there is a non babbling equilibrium, and assume without loss of generality that $\sigma(h) > \sigma(h)$. As in the proof of Proposition 6, it must be the case that (see equation 11),

$$\Pr(N_E \geq f \mid h) \geq \Pr(E : N_E = 0 \mid h)$$

Notice that for $1/2 > p_h > p_l$

$$\Pr(N_E = 0 \mid p_h) = 1 - p_h > 1/2 \text{ and } \Pr(N_E = 0 \mid p_l) > 1/2$$

and since $f(p_h, p_l) > 0$, $\Pr(N_E \geq f \mid p_h) = \Pr(N_E = 1 \mid p_h) = p_h < 1/2$ and $\Pr(N_E \geq f \mid p_l) = p_l < 1/2$. Then, given $\Pr(N_E \geq f \mid h) = \Pr(p_h \mid h)\,p_h + \Pr(p_l \mid h)\,p_l < 1/2$ and $\Pr(E : N_E = 0 \mid h) = \Pr(p_h \mid h)(1-p_h) + \Pr(p_l \mid h)\Pr(1-p_l) > 1/2$, we get

$$\frac{1}{2} > \Pr(N_E \geq f \mid h) \geq \Pr(E : N_E = 0 \mid h) > \frac{1}{2},$$

a contradiction. ■

Proof of Proposition 10. When the official observes h, from the proof of Proposition 5 we know that he will declare h iff

$$\begin{aligned}
\Pr\left(\frac{P(E\mid p_h)}{P(E\mid p_l)}\geq 1\mid h\right) &\geq \Pr\left(\frac{P(E\mid p_h)}{P(E\mid p_l)}\leq 1\mid h\right)=1-\Pr\left(\frac{P(E\mid p_h)}{P(E\mid p_l)}\geq 1\mid h\right)\Leftrightarrow \\
\Pr\left(\frac{P(E\mid p_h)}{P(E\mid p_l)}\geq 1\mid h\right) &\geq \frac{1}{2}\Leftrightarrow \Pr\left(N_E\geq \tau f\left(p_h,p_l\right)\mid h\right)\geq \frac{1}{2}.
\end{aligned}$$

But we know that for small p_h $\Pr\left(N_E\geq \tau f\left(p_h,p_l\right)\mid h\right)$ is close to 0, violating condition 1. For $\tau=1$ and $p_h<\frac{1}{2}$ equation 1 is violated, and by the proof of Propostion 5 we know that means that the official does not want to announce h when he is supposed to, because with probability larger than $1/2$ he will not be reelected. Hence, he announces l, which gets him reelected with the complementary probability. ■

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