Intergenerational Experimentation and Catastrophic Risk

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Abstract

I study an intergenerational game in which each generation experiments on a risky technology that provides private benefits, but may also cause a temporary catastrophe. I find a folk-theorem-type result on which there is a continuum of equilibria. Compared to the socially optimal level, some equilibria exhibit too much, while others too little, experimentation. The reason is that the payoff externality causes preemptive experimentation, while the informational externality leads to more caution. Remarkably, for a particular temporal discount rate, there exists an optimal equilibrium in which the behavior of two-period-lived agents align with that of an infinitely-lived social planner. In a model with a political process, unequal political power, biased towards the young, supports an optimal equilibrium most often. Extensions include finite horizon, irreversible catastrophes, and risk-aversion.

Keywords: experimentation, intergenerational equity, catastrophes, tragedy of the commons

JEL Classification: C73, D83, Q55

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> Many of the dangers we face indeed arise from science and technology—but, more frequently, because we have become powerful without becoming commensurately wise. The world-altering powers that technology has delivered into our hands now require a degree of consideration and foresight that has never before been asked of us.
>
> Carl Sagan (1994)

1 Introduction

Since the dawn of the nuclear age, humanity has come to realize that technological progress, while largely beneficial to the human condition, may also pose significant risks. Several reports (Beckstead et al., 2014; Farquhar et al., 2017; Ord, 2020) have identified these risks and concluded that they pose the greatest threats to long-term human potential—more so than any other natural risks. Bostrom (2019) makes an analogy to drawing balls out of a giant urn. Though they have mostly been favorable in the past, we will inevitably make a draw that risks destroying "the civilization that invents it."[1]

Recent events have reignited concern over risky biological studies into bio-weapons, synthetic biology, and in particular gain-of-function experiments. While natural biological risks have been responsible for the greatest death tolls in human history, misguided or accidental use of modern advancements in biotechnology have the potential to dwarf these natural death tolls (Millett and Snyder-Beattie, 2017; Nelson, 2019). Another potentially catastrophic technology, if advanced before we become "commensurately wise," is artificial intelligence. Experts have estimated that high-level machine intelligence will emerge within the next few decades and that there is a one in three chance that such development turns out to be catastrophic for humanity (Müller and Bostrom, 2016). Other risks, such as those from geoengineering (Farquhar et al., 2017) and nuclear technology,[2] may come as a consequence of our attempt to mitigate pressing climate issues without sufficient knowledge and deliberation.

This paper is concerned with these technologically-induced anthropogenic risks. How do we navigate such risks as a society in the presence of intergenerational conflict? In

[1] Bostrom calls this the "vulnerable world hypothesis."

[2] Even without its potential for catastrophe at the global scale, nuclear power has fallen out of favor in recent years, following the Fukushima disaster in 2011, the latest of the world's major nuclear-power disasters (Kormann, 2019).

other words, how do we balance the potential long-term benefits of technological progress against the risk of a global, perhaps irreversible, catastrophe when generations are short-lived and act only in their own best interest?

To this end, I study a discrete-time game of strategic experimentation[3] played by overlapping generations. The object of experimentation is a risky technology which provides private benefits to the generation using it, but may entail catastrophic costs on other generations. This payoff structure posits that motivation to pursue these risky technologies, at the end of the day, is for private *intra*generational profit, while the potential catastrophic impact is felt *inter*generationally.

The alternative technology is safe with a known payoff. This can be interpreted as a well-known, tried-and-tested technology, or as simply not using the risky technology.[4] Each generation, while they are young, makes a decision on whether or not to use the risky technology. If no catastrophe occurs, the generation may still incur costs, when they are old, from the action of the future young.

The strategic aspect of the model is twofold. First, the assumption of private benefits and public costs generates a negative *payoff externality* and brings the tragedy of the commons feature to the game. Each generation wants to *preempt* experimentation for private benefits, but does not want other generations to do so due to the public costs. Decisions to experiment fail to internalize these public costs, leading to too much experimentation in equilibrium.

Second, there is an *informational externality* between generations. Experimentation on the risky technology does not only materially affect the current generations but also provides information to later generations about its risk. Due to the informational assumption that no news is good news, non-catastrophic experimentation by the current generation invites further experimentation by later generations. This means that each generation must be *cautious* when deciding whether or not to experiment, leading to less experimentation than socially optimal. Although the material benefits go to the current generation, experimentation is informationally useful since all generations gain from better knowledge of the risks posed by a new technology.

I characterize the stationary Markov perfect equilibria of the model (Theorem 1) and find that there is a continuum of equilibria in threshold strategy, whereby a risky technology is used if and only if the current belief is below a threshold. Owing to the two types of externalities, these equilibria exhibit both too much and too little experimentation compared to a myopic equilibrium, where a decision is made based only on the current period. In standard strategic experimentation models, under-experimentation typically ensues because agents free-ride on others' information. In my model, this free-riding effect is offset

[3] See Bergemann and Välimäki (2008) for an overview of experimentation and bandit problems in economics.

[4] The model accommodates such scenarios where the choice is not between two technologies, but between using and not using a risky and potentially catastrophic technology for private gains.

by the incentive to use the risky technology for private gain, causing a generation to preempt experimentation before the next generation comes around. These opposing effects lead to the existence of both over-experimentation and under-experimentation equilibria. In Corollary 1, I show that the set of equilibria shrinks to the myopic equilibrium as the social discount factor decreases. Analogous to the ability to sustain cooperation in an infinitely-repeated prisoner's dilemma, the possibility of intergenerational cooperation, represented here by optimal experimentation, rests on the social discount rate.

I then characterize the optimal level of experimentation in Theorem 2 by solving the discounted utilitarian social planner's problem. I show that the value function is piecewise linear and that the optimal policy is also a threshold policy. This means that if the initial belief is below a certain threshold, the risky technology is used in perpetuity or until a catastrophe occurs. If initial belief is above a threshold, then the safe technology is used in perpetuity.

Both the equilibrium and the optimal policy exhibit threshold behavior. Assuming that society has the ability to change initial belief and that this ability does not come around very often, the equilibrium and the optimal policy dynamics echo Derek Parfit's comment that we are living at "the hinge of history."[5]

To gauge how much generational agency hinders long-term ideal, I compare the equilibrium and the optimal policy. Since there is a continuum of equilibria, there may exist one that coincides with the optimal policy. This is a surprising, yet sensitive, result. On one hand, it is remarkable that a sequence of selfish short-lived agents behaves in accordance with an infinitely-lived social planner. On the other hand, other variations of the model do not have this feature. The underlying forces need to counterbalance in just the right way for selfish short-run incentives to align with the optimal long-run solution.

Theorem 3 asserts that the existence of an optimal equilibrium depends on the value of the social discount rate. Specifically, an optimal equilibrium may not exist when the discount rate is too high or too low. When the discount rate is too high, both the planner and the generations are myopic in the sense that they care more about their immediate futures. However, the immediate future for each generation is only their own lifetime, while the immediate future of the planner takes into account another generation as well. This is the payoff externality at work. When the discount rate is too low, incentives are misaligned again, but this time, due to the informational externality. The generations

[5] Parfit (2011) writes:

> We live during the hinge of history. Given the scientific and technological discoveries of the last two centuries, the world has never changed as fast. We shall soon have even greater powers to transform, not only our surroundings, but ourselves and our successors. If we act wisely in the next few centuries, humanity will survive its most dangerous and decisive period. Our descendants could, if necessary, go elsewhere, spreading through this galaxy.

For a book-length exposition of this idea tied to existential risk, see Ord (2020), who calls this hinge the "precipice."

only care about their lifetime payoffs, while the planner also cares about the informational benefit that results from using the risky technology.

To remedy the payoff externality, I propose a political process that lends some political power to the old. First, I investigate whether two living generations can work together—mimicking an outcome of an equal power political process—to achieve a better outcome. Unfortunately, equal power results in an even worse outcome since only under-experimentation remains (Proposition 1). Tension between the young and the old seems to be crucial for any hope of optimal experimentation. However, if the political power were not equal, then there is scope for improvement (Proposition 2). Allowing for an optimal share of power between the young and the old helps resolve the payoff externality—there is no more over-experimentation for low discount factor. Under-experimentation for high discount factor nevertheless persists (Theorem 4).

I then consider extensions to the baseline model. Proposition 3 considers the finite-horizon version of the game and shows that only the myopic equilibrium survives, supporting the folk theorem interpretation. In Proposition 4, I remove the payoff externality and show that without it only under-experimentation arises in equilibrium. In addition, I analyze a model where the damage from a catastrophe lasts for many periods. Proposition 5 characterizes both the equilibrium and the optimal policies for a model where the catastrophe is irreversible. Lastly, I allow for risk aversion and show that it impacts the results only insofar as it changes the magnitude of the parameters.

The paper is related to several strands of literature. It first belongs to the large literature on the economics of climate change and other catastrophes.[6] Typically, climate change and catastrophes are studied in economics with the Integrated Assessment Models (IAMs), in which a dynamic economy affects the climate through a damage function, and vice versa. More consumption today means worse climate outcomes tomorrow, lowering tomorrow's output and consumption (Nordhaus and Boyer, 2000; Nordhaus, 2008; Hassler and Krusell, 2012; Golosov et al., 2014). The goal in these models is to find an optimal path that balances consumption today with damages and consumption tomorrow. Another approach to the economics of catastrophes is to ask how one should distribute resources to mitigate these risks. Martin and Pindyck (2015, 2021) show that simple cost-benefit analysis may not work when dealing with such large projects.

The approach taken here is quite different.[7] I focus on technologically-induced anthropogenic catastrophic risks and use the strategic experimentation framework as a basis. Strategic experimentation, as pioneered by Bolton and Harris (1999) and Keller et al.

[6] For general audience discussion, see Nordhaus (2013); Wagner and Weitzman (2016); Pindyck (2021).

[7] The model cannot be used to crunch out numbers for policy recommendations like the IAMs, but I believe it can nonetheless help understanding keys forces behind intergenerational conflicts. Alas, as argued convincingly by Pindyck (2013, 2017), none of the IAMs can offer any realistic policy implications either as there are too many unknowns, uncertainties, and ambiguities when it comes to the big and long-term global problems.

(2005), concerns a game-theoretic model of the trade-off between acquiring more information and making the correct decision. The current paper investigates a discrete-time version of Keller and Rady (2015), with two main modifications. First, the breakdown costs are assumed to be incurred by all agents. This reflects the nature of catastrophic risks. Second, the overlapping generation structure of the game is taken to better reflect an intergenerational problem.

This leads to a final strand of literature: intergenerational games. The idea of intergenerational gaming was proposed in the seminal discussion on intergenerational equity by Phelps and Pollak (1968) in the context of optimal savings. The idea subsided, but has been revived by Arrow's "agent-relative ethics" (1999). Since then, some papers have studied intergenerational games, typically in the climate context, where the conflict between generations comes from misaligned time perspectives (Karp and Tsur, 2011; Karp, 2017; Gerlagh and Liski, 2018b). The intergenerational conflict in my model comes instead from the public nature of the costs and from the informational externality between generations. The overlapping generational structure I adopt in this paper is inspired by Acemoglu and Jackson (2015), where it was used to study the evolution of social norms.

The papers closest to mine combine the three strands of literature: catastrophes, experimentation, and intergenerational payoff conflicts. Gerlagh and Liski (2018a) add learning to a climate-economy model. The informational structure they consider is the same as mine, but catastrophes occur exogenously and learning is passive—belief is updated automatically in each period if no catastrophe occurs. Gerlagh and Liski (2018a) solve for the optimal policy and the optimal carbon price before and after the catastrophe occurs. Lastly, Liski and Salanié (2020) and Guillouet and Martimort (2020) incorporate active experimentation in a dynamic optimization problem, where experimentation contributes to a stock which may trigger a catastrophe if it exceeds an unknown threshold. The catastrophe, once triggered, impacts the society at a stochastic delay. Both papers solve for the optimal policy before and after a catastrophe is triggered. There is no strategic interaction in the former paper, while strategic interaction arises between time-inconsistent selves in the latter. The setting of the current paper has no delays nor time-consistencies. The focus of this paper is on the interactions between short-lived sequential strategic generations and on how the outcomes compare to the long-run social optimum.

The rest of the paper is organized as follows. I set up the model and introduce pertinent definitions in Section 2. Section 3 characterizes the equilibrium of the intergenerational experimentation game. Section 4 solves for the social planner's optimal solution and discusses the relationship between the equilibrium and the optimal solutions. I extend the model to allow for a political process in Section 5. Section 6 considers other extensions and variations. Section 7 concludes. All proofs are relegated to Appendix A, while Appendix B analyzes a two-period version of the model with added features.

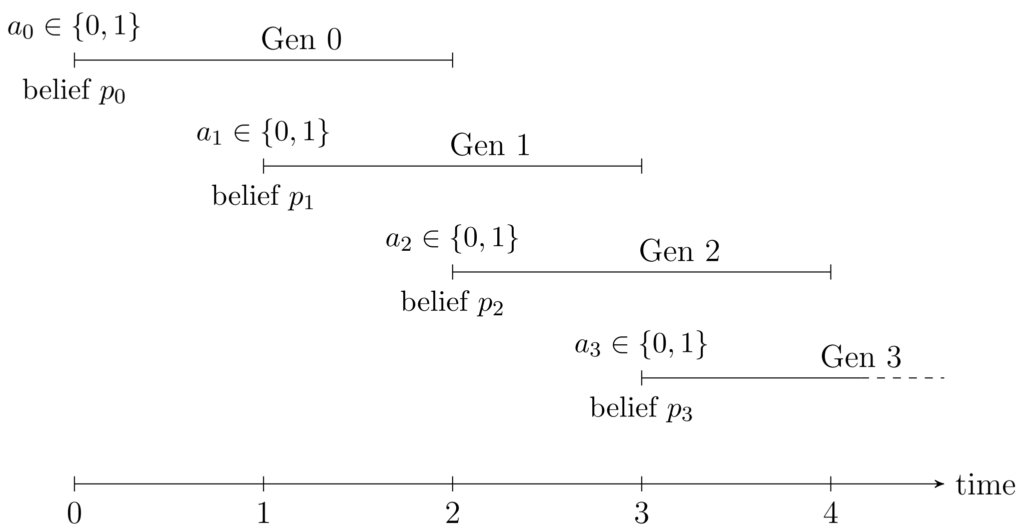

Figure 1: Structure of Overlapping Generations.

2 The Model

This section sets up the model, the belief dynamics, and state pertinent definitions.

2.1 Set Up

Time is discrete and starts at $t = 0$. Players (also, generations) are indexed by the time they are born, $t \in \{0, 1, \dots\}$. Each generation t lives for two periods, t and $t+1$. At time t, when they are young, generation t makes a decision between two technologies: a safe technology or a risky technology that comes with certain private benefits and uncertain public costs. Denote $a_t \in \{0, 1\}$ to be generation t's usage of the risky technology (experimentation) at time t. In the next period, at time $t + 1$, generation t does not benefit from the technology, though they may suffer costs associated with a catastrophe caused by the current young, generation $t+1$. Payoffs are discounted at the *social discount factor* $\delta \in (0, 1)$. The structure of generations is depicted in Figure 1.

The net benefits of the safe technology[8] is zero. On the other hand,[9] the risky technology yields certain benefits $s \in (0, 1)$ to the generation using it, but can potentially cause a global catastrophe—a temporary public damage of 1.[10] The possibility of this

[8]In the context of resource extraction, this is a technology that is known to be safe and clean, such as solar and wind power. In the context of artificial intelligence research, one can interpret safe technology simply as not advancing its capability until society learns more about its potential dangers.

[9]"Arm" is perhaps more appropriate than "hand" in the current context.

[10]Section 6.3 considers a model with long-term damage, lasting for many, and potentially all, future generations. The assumptions that the safe technology has zero net benefits and that the catastrophic damage is 1 are just normalizations. Suppose that the net benefits of the safe technology is $b > 0$, then we can redefine the benefits of the risky technology as $b+s$. A larger damage, say of $X > 1$, can be captured by redefining the benefits of the risky technology from s to s/X. Another strategically equivalent model is the one where in each period the generation is faced with a choice between two costly technologies to generate a fixed income: the safe technology costs s, while the risky technology costs 0 if there is no

catastrophe depends on a persistent unknown *state of the world*, $\omega \in \{\mathcal{G}, \mathcal{B}\}$. If the state of the world is good, $\omega = \mathcal{G}$, a catastrophe never happens and the risky technology costs 0. If the state of the world is bad, $\omega = \mathcal{B}$, a catastrophe occurs with probability $\lambda_t a_t$, where $\lambda_t \in [0,1]$ is the *fragility* of the technology.[11] If λ_t is high, then the technology gets out of control and a catastrophe occurs easily. If λ_t is low, then the technology is less fragile.

For tractability, I assume in this paper that the fragility is constant over time, $\lambda_t = \lambda \in [0,1]$ for all t.[12] I further assume that $\lambda > s$, so a revelation that the state of the world is bad ensures no further experimentation. This implies that once a catastrophe occurs, all generations thereafter stick to the safe technology.

2.2 Beliefs

A common prior belief that the state of the world is bad is $p_0 = \mathbb{P}(\omega = \mathcal{B}) \in (0,1)$. Let p_t be the belief that the state of the world is bad at the beginning of period t, before any decision is made. After generation t's decision, either a catastrophe occurs or it does not. If a catastrophe occurs, belief jumps to $p_{t+1} = 1$ and the game effectively ends.[13] If not, belief evolves according to Bayes' rule:

$$p_{t+1}(\boldsymbol{a}^{t+1}) = \frac{p_t(1-\lambda a_t)}{p_t(1-\lambda a_t) + 1 - p_t} = \frac{p_0 \prod_{s=0}^{t}(1-\lambda a_s)}{p_0 \prod_{s=0}^{t}(1-\lambda a_s) + (1-p_0)}, \tag{2}$$

catastrophe and costs 1 otherwise. The objective there is then to minimize the costs, but it is essentially the same model.

[11] This is the arrival rate of the Poisson process governing the catastrophic event. In the current context, the fragility can be thought of as a function of two components that work in opposite directions. First, how tolerant the technology is to alteration and experimentation before it goes wrong contributes negatively to fragility. In this sense, the good state can be thought of as the situation when the technology is infinitely tolerant, making $\lambda_t = 0$ for all t. In the bad state of the world, it is conceivable that the tolerance decreases overtime, perhaps due to increased hostile motivation and accumulated errors. Second, the state of our collective wisdom also contributes to the fragility. It is conceivable that society progresses in such a way that we become "commensurately wise" in handling powerful technologies, lowering λ_t over time. See discussion in Mann (2018) on the competing forces of technological advancement and the environment.

[12] This is a common assumption in the literature as it lends stationarity to the dynamic problem: given that an event has not occurred in the past, the probability that it will occur in the next instance is constant. This assumption should be addressed in future research. One way to do this and capture the tension between technological and moral progresses is to treat λ_t as a state variable that evolves according to the players' actions. Fragility can be thought of as a stock that depreciates when there is no experimentation and edges closer to 1 with each generation's experimentation:

$$\lambda_{t+1} = \gamma\lambda_t + (1-\gamma)[(1-a_t)s + a_t], \tag{1}$$

for some $\gamma \in [0,1]$ and $\lambda_0 = \lambda \in [0,1]$, with $\lambda > s$. To get a glimpse at how the results change with varying λ_t, Appendix B considers a two-period model with $\lambda_1 \neq \lambda_2$.

[13] Since the state is revealed to be bad, all generations thereafter will only use the safe technology.

where $\boldsymbol{a}^{t+1} = (a_0, \ldots, a_t)$ is the history of actions chosen before period $t+1$. For notational convenience denote, for $k \le t+1$,

$$\boldsymbol{a}_k^{t+1} = (\underbrace{1, \ldots, 1}_{k}, \underbrace{0 \ldots, 0}_{t+1-k}). \tag{3}$$

to be a history with k uses of the risky technology followed by $t+1-k$ uses of the safe technology. For such histories, belief simplifies to

$$p_{t+1}(\boldsymbol{a}_k^{t+1}) = \frac{p_0(1-\lambda)^k}{\rho(k, p_0)} \quad \text{where} \quad \rho(k, p) \equiv p(1-\lambda)^k + (1-p). \tag{4}$$

We say that a belief p is *optimistic* when p is low because this indicates that the good state of the world is more likely. On the other hand, we say that a belief is *pessimistic* if p is high.

2.3 Strategies, Equilibrium, and Payoff

The solution concept I use is that of Markov perfect equilibrium, where each generation t follows a Markov strategy $a_t = \alpha_t(p_t)$ for some $\alpha_t : [0, 1] \to \{0, 1\}$ with belief p_t as the state variable. Let $\mathcal{A}$ be the set of all Markov strategies that map a state p to a decision on whether or not to experiment. A *Markov perfect equilibrium* (MPE) is a profile of Markov strategies $\boldsymbol{\alpha}^* = (\alpha_t^*)_t$, $\alpha_t^* \in \mathcal{A}$ which constitutes a subgame perfect equilibrium. A *stationary* Markov perfect equilibrium[14] (SMPE) is an MPE in which strategies do not depend on time. That is, all generations use the same Markov strategy, $\alpha_t^* = \alpha^* \in \mathcal{A}$ for all t. I restrict attention to characterizing SMPEs in this paper and let $\mathcal{A}^* \subset \mathcal{A}$ be the set of all Markov strategies that constitute an SMPE.

An important class of Markov strategies are threshold strategies, which can be described, for some threshold $\bar{p}$, by: "use the risky technology if belief p is more optimistic than $\bar{p}$, otherwise use the safe technology." More precisely, denoting $\bar{\mathcal{A}} \subset \mathcal{A}$ as the set of threshold strategies, then $\alpha_{\bar{p}} \in \bar{\mathcal{A}}$ is a Markov strategy of the form

$$\alpha_{\bar{p}}(p) = \begin{cases} 1 & \text{if} \quad p \le \bar{p} \\ 0 & \text{if} \quad p > \bar{p} \end{cases} \tag{5}$$

for some $\bar{p} \in [0, 1]$. A *threshold* Markov perfect equilibrium is an MPE in which all generations use a threshold Markov strategy. It will be shown that all SMPEs are threshold MPEs.

The payoff of generation t consists of several terms. First, sa_t is the private benefits

[14] In the current setting, "S" could also stand for "symmetric," where a *symmetric* MPE is one in which all players use the same strategy. They coincide in this set up. Moreover, with a minor abuse of notation, I say $\alpha^* \in \mathcal{A}$ constitutes an MPE when indeed $\boldsymbol{\alpha}^* = (\alpha^*)_t$ is an MPE.

from experimentation. With probability $p_t \lambda a_t$, a catastrophe occurs, incurring a unit cost to the generation. If so, $p_s = 1$ for all $s > t$ and the next generation will use the safe technology, $a_{t+1} = 0$ since $\lambda > s$.[15] If no catastrophe occurs now, generation t may still incur a cost at time $t + 1$, discounted by $\delta \in (0, 1)$, caused by generation $t + 1$'s use of the risky technology. Thus, generation t's payoff is

$$u_t = (s - p_t \lambda) a_t - \delta(1 - p_t \lambda a_t) p_{t+1} \lambda a_{t+1}. \tag{6}$$

2.4 Discussion of the Model

The assumption that the risky technology provides private benefits to the young, but may incur costs to both the old and the young is central to the model. The first part of the assumption is evidently plausible. It holds when risky research is conducted by a profit-seeking party, which is generally true in the current economic climate where big technological and pharmaceutical firms drive the research frontiers in artificial intelligence and biotechnology.

The second part of the assumption, that the old are affected by the actions of the young is unique to this paper. This makes a generation more risky when they are young and more conservative when they are old, the opposite sentiment to the typical narrative in intergenerational conflicts. In overlapping generations models with debt accumulation or climate exploitation, the old (politicians) are the ones (politically) benefiting from risky decisions—through more spending and consumption. Since they will not be around when the bill comes due, excessive debt and unmitigated carbon emissions are the usual conclusions. In those contexts, the young are the environmentally conservative ones, trying to stop the risky actions that privately benefit the old.

This paper is concerned with technologically-induced anthropogenic risks. For these risks, the dynamics are reversed: it is the young who privately benefit from risky actions. The old, on the other hand, do not materially benefit from these decisions and thus care exclusively about avoiding catastrophes. Being beyond career ambition and corporate profits, the old value society's well-being above small gains from technological advancements. An alternative interpretation of the timing structure is that the old represent the altruistic utility of a one-period-lived generation. In this interpretation, generation t cares about the direct offspring in period $t + 1$, but only to the extent that they do not suffer from a catastrophe.

Furthermore, the model supposes that the generation makes a decision when they are born. It is without loss of generality if the generations live for some periods before taking the action. All payoff-relevant effects from previous actions are captured in the public belief at time t. For instance, the model can be modified to have three-period-lived

[15] Since belief now stays at $p_s = 1$ for all $s > t$, in equilibrium the next generation chooses $\alpha(1) \in \{0, 1\}$ to maximize $(s - \lambda)\alpha(1) - \delta\lambda\alpha(1)$.

generations, where they make decisions in the second period. The only change this would have is in the optimal policy since a catastrophe now affects three generations rather than two. Equilibrium behavior would not change, so as a consequence there would be a larger discrepancy between the equilibrium and the optimal policy.

3 Equilibrium Analysis

This section analyzes the model. After some preliminary results, I characterize the equilibrium of the game and show that there is a continuum of SMPEs. Furthermore, I note a folk-theorem-type behavior that patience leads to a larger set of equilibria.

3.1 Preliminary Analysis

Belief thresholds play a key role in the results of the paper. Hence, I list them here for easy reference. For ease of notation, I drop explicit dependence on s, λ, and δ as appropriate.

Decisions are *myopic* when they only take into account the current period payoff. The following two belief thresholds are, respectively, what a myopic generation and a myopic social planner would use to decide on the risky technology:

$$p^m(s,\lambda) \equiv \frac{s}{\lambda} \qquad \text{(myopic threshold of each generation),}$$
$$p^M(s,\lambda) \equiv \frac{s}{2\lambda} \qquad \text{(myopic threshold of the social planner).}$$

As will be shown in Theorem 1, the model has a continuum of SMPEs in threshold strategies. Thus, the continuum is defined by an interval of belief thresholds. The smallest equilibrium threshold is either

$$p^\dagger(s,\lambda) \equiv \frac{s}{\lambda}\frac{1-\lambda}{1-s} \qquad \text{(smallest equilibrium threshold candidate 1)}$$

or

$$\check{p}(s,\lambda,\delta) \equiv \frac{s}{\lambda(1+\delta(1-\lambda))} \qquad \text{(smallest equilibrium threshold candidate 2)}$$

depending on the parameters of the model, while the largest equilibrium threshold is given by

$$\hat{p}(s,\lambda,\delta) \equiv \frac{s}{\lambda(1-\delta\lambda)} \qquad \text{(largest equilibrium threshold).}$$

Lastly, the social planner uses a different belief threshold for deciding on the optimal use

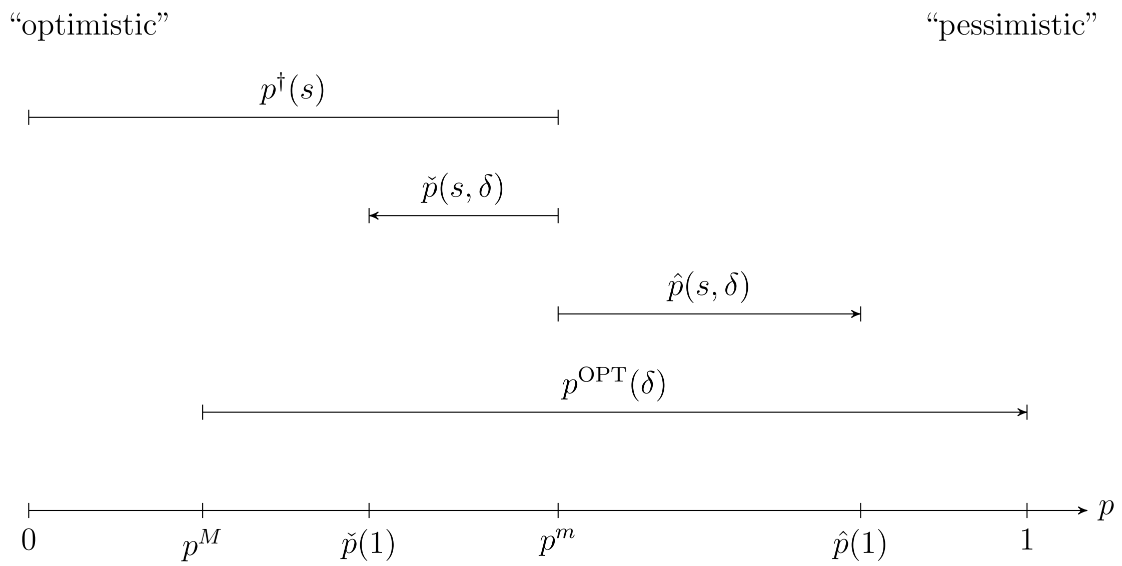

Figure 2: Threshold Values.

of the risky technology. Section 4 derives the following:

$$p^{\mathrm{OPT}}(s,\lambda,\delta) \equiv \frac{s}{\lambda}\frac{\delta\lambda + (1-\delta)}{\delta s + (1-\delta)2} \qquad \text{(optimal threshold of the social planner).}$$

To prepare for subsequent sections which explore how myopic, equilibrium, and optimal behaviors relate to each other, I compare these beliefs with respect to the parameters of the model. The following lemma orders these beliefs with respect to the discount factor δ.

Lemma 1. *With respect to δ, the following holds:*

(i) $p^M < \check{p}(\delta) < p^m$ *and* $\check{p}(\delta)$ *is strictly decreasing with* $\check{p}(\delta) \to p^m$ *as* $\delta \to 0$.

(ii) $p^m < \hat{p}(\delta)$ *and* $\hat{p}(\delta)$ *is strictly increasing with* $\hat{p}(\delta) \to p^m$ *as* $\delta \to 0$.

(iii) $p^M < p^{OPT}(\delta)$ *and* $p^{OPT}(\delta)$ *is strictly increasing with* $p^{OPT}(\delta) \to p^M$ *as* $\delta \to 0$ *and* $p^{OPT}(\delta) \to 1$ *as* $\delta \to 1$. *Moreover,* $p^{OPT} \geq p^m$ *if and only if* $\delta \geq \frac{1}{1+(\lambda-s)}$.

(iv) $p^{\dagger} < p^m$ *and* $p^{\dagger} \geq \check{p}(\delta)$ *if and only if* $\delta \geq \frac{\lambda-s}{(1-\lambda)^2}$.

The relationships between these quantities are depicted in Figure 2, where for quantities that depend on δ, the direction of the arrow indicates increasing δ. Lemma 2 characterizes the properties of these beliefs with respect to s and λ.

Lemma 2. *With respect to s and λ, the following holds:*

(i) p^m, p^M, $\check{p}(\delta)$, $\hat{p}(\delta)$, *and* $p^{OPT}(\delta)$ *are increasing in* s.

(ii) p^m, p^M, $\check{p}(\delta)$, *and* $p^{OPT}(\delta)$ *are decreasing in* λ.

(iii) $\hat{p}(\delta)$ *is decreasing in* λ *if* $\lambda \leq 1/2\delta$*. Otherwise,* $\hat{p}(\delta)$ *is increasing in* λ*.*

(iv) $p^{\dagger}$ *is decreasing in* λ*, increasing in* s*, approaches* 0 *as* $|\lambda - s| \to 1$*, and approaches* p^m *as* $|\lambda - s| \to 0$*.*

I now proceed with the equilibrium characterization.

3.2 Equilibrium Characterization

Generation t's problem is to choose whether or not to experiment. To characterize a stationary Markov perfect equilibrium, we seek a Markov strategy $\alpha : [0,1] \to \{0,1\}$ such that if $a_s = \alpha(p_s)$ for all other generations $s \neq t$, then $a_t = \alpha(p_t)$ is a best-response. The problem is to choose $\alpha^* \in \mathcal{A}$ such that, for all p,

$$\alpha^* = \arg\max_{\alpha(\cdot)} \, (s - p\lambda)\alpha(p) - \delta(1 - p\lambda\alpha(p))p'\lambda\alpha^*(p'), \tag{7}$$

where $p' = p(1 - \lambda\alpha(p))/(1 - p\lambda\alpha(p))$ is the next period's belief. It turns out that there is a continuum of SMPEs, each with a threshold strategy.[16]

Theorem 1. $\alpha \in \mathcal{A}^*$ *if and only if* $\alpha = \alpha_{\bar{p}} \in \bar{\mathcal{A}}$ *with*

$$\bar{p} \in \bar{P}(s,\delta) \equiv \left[\max\left\{\check{p}(s,\delta), p^{\dagger}(s)\right\}, \hat{p}(s,\delta)\right]. \tag{8}$$

In this conclusive bad news model of experimentation, belief $p < 1$ either stays the same, transitions downward, or jumps to 1. The SMPEs characterized in Theorem 1 are all in threshold strategies which imply that the initial belief p_0 governs the whole dynamics of equilibrium. Optimistic beliefs lead to experimentation since a catastrophe is less likely, while pessimistic beliefs lead to more caution and no experimentation. If $p_0 \leq \bar{p}$, then all generations, conditioning on not having had a catastrophe, experiment. Belief will be driven down to be more and more optimistic, leading to further experimentation, before almost surely jumping to 1 if the true state is bad. If $p_0 > \bar{p}$, then the initial belief is sufficiently pessimistic to deter experimentation. The initial generation does not experiment, nor do any generations thereafter. In this case, no generation learns the state of the world—a missed opportunity if the state turns out to be good.

The continuum of SMPEs covers a range of threshold beliefs. When the threshold is low, initial belief must be quite optimistic to invoke perpetual experimentation. Some pessimism is enough to anchor society in the state of no experimentation. In a sense, there is "less" experimentation when the threshold is low. The opposite is true when the threshold is high. A slightly optimistic initial belief—that the world is in a good

[16] All threshold MPEs are also stationary. There may however be non-stationary, non-threshold MPEs. This is a direction of future research.

state—will set off experimentation ad infinitum (or at least until a catastrophe occurs). Thus, there is "more" experimentation when the threshold is high.

Importantly, there are equilibria that are more optimistic and ones that are more pessimistic than the myopic equilibrium where all generations use the myopic threshold, p^m. Both types of equilibria have some intuitive appeal. I call an equilibrium with threshold $\bar{p} \leq p^m$ a *cautious* SMPE, while those with $\bar{p} > p^m$ are called *preemptive* SMPEs. The reasoning is as follows.

The equilibrium with the lowest threshold $\max\{\check{p}(s,\delta), p^\dagger(s)\}$ is lower—and therefore more optimistic—than the myopic threshold, p^m. Equilibria near the lower end are cautious and exhibit lower experimentation because of the *informational externality*.[17] Experimentation provides information for later generations about the risky technology. Due to the informational assumption of the model, experimentation by the current generation encourages further experimentation by later generations since conditional on the absence of a catastrophe each generation becomes more optimistic than the last. This means that each generation must be overly cautious when deciding whether or not to experiment. Intuitively, they reflect the thinking: "if I (the current generation) experiment now, it will invite you (the next generation) to experiment even more in the future, so I should be more cautious!"

On the other hand, the highest threshold equilibrium $\hat{p}(s,\delta)$ is higher—more pessimistic—than the myopic threshold. Equilibria near this upper threshold encourages experimentation and intuitively reflect preemptive behaviors: "if you (the next generation) are going to sabotage the world, then I (the current generation) would rather do so now and get some of the benefits!" This is due to the *payoff externality* in the game. Private benefits incentivize each generation to experiment, despite the public costs of doing so. This creates an intergenerational tragedy of the commons. In Section 6.2, I examine a model without the payoff externality and show that cautious and preemptive equilibria cease to exist.

3.3 A Folk Theorem

A corollary to Theorem 1 is that patience enlarges the set of equilibria, while impatience shrinks it to the singleton which only contains the myopic equilibrium. In a sense, the myopic equilibrium is the most robust equilibrium. This result has the flavor of a folk theorem.

Corollary 1. *For $\delta < \delta'$, $\bar{P}(s,\delta) \subseteq \bar{P}(s,\delta')$. The set $\bar{P}(s,\delta)$ shrinks to $\{p^m\}$ as $\delta \to 0$.*

The game we are analyzing is a stochastic game, which is a repeated game with a payoff-relevant state variable that evolves based on the players' actions. In addition, in

[17] This is also due to the payoff externality since without it, there is no linkage between the generations rendering the informational externality ineffective.

this paper players play sequentially and each player plays only once. Viewed through this lens, Corollary 1 is a folk theorem for this special case of stochastic games.[18] This interpretation is strengthened by the fact that when there is a definite end date to the game the continuum of equilibria vanishes and only the myopic equilibrium survives. This will be shown in Section 6.1 when we look at a finite-horizon version of the model.

4 Social Welfare

As a benchmark, I solve the social planner's problem. I show that the planner's solution is also a threshold policy. I further show that equilibrium and optimal behaviors align for intermediate social discount rates. Moderate impatience is good for intergenerational welfare.

4.1 Social Planner's Problem

A *discounted utilitarian* social planner[19] chooses a sequence of actions $\boldsymbol{a} = (a_t)_t$ to maximize the discounted sum of all generations' payoffs. The problem can be solved as if time ends after a catastrophe has occurred. This is because if a catastrophe occurs the optimal action thereafter is to not experiment, rendering a zero continuation value. At a given time t, expected payoff of the current young generation is $(s - p_t\lambda)a_t$. Since a catastrophe is an externality, we must also account for the expected payoff of the current old, which is $-p_t\lambda a_t$. Thus, the planner's payoff at time t, conditioning on the event that no catastrophe had occurred, is $(s - p_t\lambda 2)a_t$.

Define a sequence of random variables $\{\chi_t\}_t$, where χ_t takes value 1 if a catastrophe had not occurred by time t, and takes values 0 otherwise. χ_t reflects the catastrophic risk in the model and it plays a role of additional discounting as it enters the planner's payoff together with discounting from pure time preference, δ. Thus, given the prior $p_0 = p$ and the sequence of actions $\boldsymbol{a}$, the planner's payoff is:

$$W(\boldsymbol{a}, p) = \mathbb{E}_p\left[(1-\delta)\sum_{t=0}^{\infty}\delta^t\chi_t\left(s - \mathbb{1}_{\{\omega=\mathcal{B}\}}\lambda 2\right)a_t\right], \tag{9}$$

where the expectation is taken over the processes $\{p_t\}_t$ and $\{\chi_t\}_t$. Let $V(p)$ denote the value function of the social planner's problem, then

$$V(p) = \sup_{\boldsymbol{a}} W(\boldsymbol{a}, p). \tag{10}$$

[18] See Shapley (1953) for a background on stochastic games. For a general analysis of folk theorem in stochastic games under different assumptions see, for example, Dutta (1995) and Bhaskar et al. (2013).

[19] I make such a distinction because in Section 5 I consider a game between short-lived planners. A short-lived planner is someone who cares only about the welfare of the people during their own period. As will be shown, this mimics the behavior of a fair political process.

Note that $V(p) \geq 0$ since the planner can always prescribe $\boldsymbol{a} = \mathbf{0}$. Theorem 2 solves for the value function and shows that the optimal solution is a threshold policy.

Theorem 2. *The value function $V(p)$ is piecewise linear and decreasing in p,*

$$V(p) = \max\left\{ s - p\lambda \frac{\delta s + (1-\delta)2}{\delta\lambda + (1-\delta)}, 0 \right\}. \tag{11}$$

The optimal policy is a threshold policy $\alpha_{p^{OPT}}$, where

$$p^{OPT}(\delta) \equiv \frac{s}{\lambda} \frac{\delta\lambda + (1-\delta)}{\delta s + (1-\delta)2}. \tag{12}$$

Theorem 2 means that if the prior belief $p_0 \leq p^{\mathrm{OPT}}$, then generations should experiment in perpetuity, or until a catastrophe occurs. If $p_0 > p^{\mathrm{OPT}}$, then no generation should experiment, fixing belief at p_0 forever. In the language of state transition, given the optimal policy, states $p > p^{\mathrm{OPT}}$ are absorbing, while states $p \leq p^{\mathrm{OPT}}$ transition downward before jumping to 1 almost surely if the state of the world is bad.

Some remarks on p^{OPT} are in order. First, $\partial p^{\mathrm{OPT}}/\partial s > 0$ and $\partial p^{\mathrm{OPT}}/\partial \lambda < 0$. An increase in the benefits of experimentation leads to more pessimistic threshold—the initial belief that the state of the world is bad must be quite high to not trickle down a wave of experimentation. The opposite is true for an increase in fragility λ. If a catastrophe occurs easily, then one should be more cautious. Second, and more interestingly, is the fact that more patience leads to more experimentation in the optimal solution since p^{OPT} is increasing in δ (see Lemma 1). As $\delta \to 0$, $p^{\mathrm{OPT}} \to p^M \equiv \frac{s}{2\lambda}$, the myopic threshold for the social planner. Acting myopically, experimentation is worth while if the benefits s outweighs the expected cost $p\lambda 2$. As $\delta \to 1$, $p^{\mathrm{OPT}} \to 1$, so in the limit of intergenerational equity, the optimal policy prescribes experimentation for all initial beliefs. Moreover, depending on δ, p^{OPT} may or may not coincide with any equilibrium thresholds—this is explored further in Section 4.2.

To understand the optimal policy more intuitively, write the value function[20] as:

$$V(p) = \max\left\{ (1-\delta)\tilde{\Omega}(p), 0 \right\}, \tag{13}$$

where

$$\tilde{\Omega}(p) \equiv \sum_{k=0}^{\infty} \delta^k \Omega(k,p) \tag{14}$$

and

$$\Omega(k,p) \equiv s\rho(k,p) - 2p\lambda(1-\lambda)^k = p(1-\lambda)^k(s-2\lambda) + (1-p)s. \tag{15}$$

The quantity $\Omega(k,p)$ is interpreted as the expected payoff of the current period when all

[20] This is derived in the proof of Theorem 2.

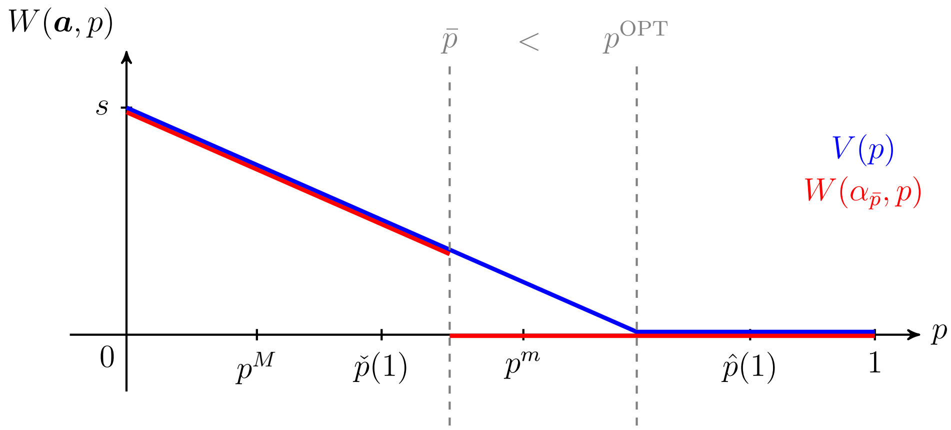

Figure 3: Equilibrium and Optimal Social Values with $\bar{p} < p^{\text{OPT}}$.

previous generations have experimented. Its properties are as follows.

Lemma 3. $\Omega(k, p)$ *has the following properties:*

(i) For all k, $\Omega(k, 0) = s$.

(ii) For all k, $\partial\Omega(k, p)/\partial p < 0$ and $\Omega(k, p) \to (1 - \lambda)^k (s - 2\lambda) < 0$ as $p \to 1$.

(iii) For all p, $\partial\Omega(k, p)/\partial k > 0$ and $\Omega(k, p) \to (1 - p)s > 0$ as $k \to \infty$.

First, $\tilde{\Omega}(p)$ converges for all p. By (ii) of Lemma 3, it strictly decreases in p. Moreover, by (i) and (ii), there exists a belief such that $\tilde{\Omega}(p)$ equals zero. This is indeed the optimal threshold p^{OPT}. To see that the optimal threshold must be more pessimistic—larger—than the planner's myopic threshold p^M, note that by (iii), $\Omega(k, p^M) > 0$ for all $k > 0$ since $\Omega(0, p^M) = 0$. Hence, $\tilde{\Omega}(p^M)$ is necessarily strictly positive and a small increase to $p^M + \epsilon$ would still allow it to be positive. At $p^M + \epsilon$, the early $\Omega(k, p^M + \epsilon)$ terms are negative, but as long as later terms are large enough to compensate, $\tilde{\Omega}(p^M + \epsilon)$ would still be greater than zero. How large ϵ can be depends on the planner's patience δ.

The intuition is that if the planner cares about future generations, then even if the state of the world is likely bad, it is worthwhile for the first few generations to bet against it and learn more about the state. The hope is that the state of the world is actually good, allowing future generations to benefit from the new technology without much risk.

4.2 Discount Rate and Efficiency

I now compare optimal and equilibrium outcomes through the lens of the social discount factor, δ. Given an MPE $\boldsymbol{\alpha}^*$, $W(\boldsymbol{\alpha}^*, p)$ is the social value of the MPE. By definition, $V(p) \geq W(\boldsymbol{\alpha}^*, p)$ and $V(p) \geq 0$. However, as will be shown, $W(\boldsymbol{\alpha}^*, p)$ may be negative for some equilibrium.

Consider an SMPE $\alpha_{\bar{p}}$. There are three possibilities:

– If $\bar{p} = p^{\mathrm{OPT}}$, then the social values coincide, $V(p) = W(\alpha_{\bar{p}}, p)$. The amount of experimentation is just right.

– If $\bar{p} < p^{\mathrm{OPT}}$, then the equilibrium exhibits too little experimentation. With initial belief $p_0 \in (\bar{p}, p^{\mathrm{OPT}})$, generations do not experiment, while the social planner would have wanted them to since this would generate information that would be helpful for all generations to come. I call this *under-experimentation*. Figure 3 shows the optimal social value $V(p)$ and the equilibrium social value $W(\alpha_{\bar{p}}, p)$ for this case.

– If $\bar{p} > p^{\mathrm{OPT}}$, then the equilibrium exhibits too much experimentation. For $p_0 \in (p^{\mathrm{OPT}}, \bar{p})$, all generations experiment, but they would have been better off not doing so. Over-experimentation for intermediate values of p_0 leads to a negative social value. The option to choose the risky technology causes society to be worse off than it would have been otherwise. I term this *over-experimentation*. Figure 4 depicts this case.

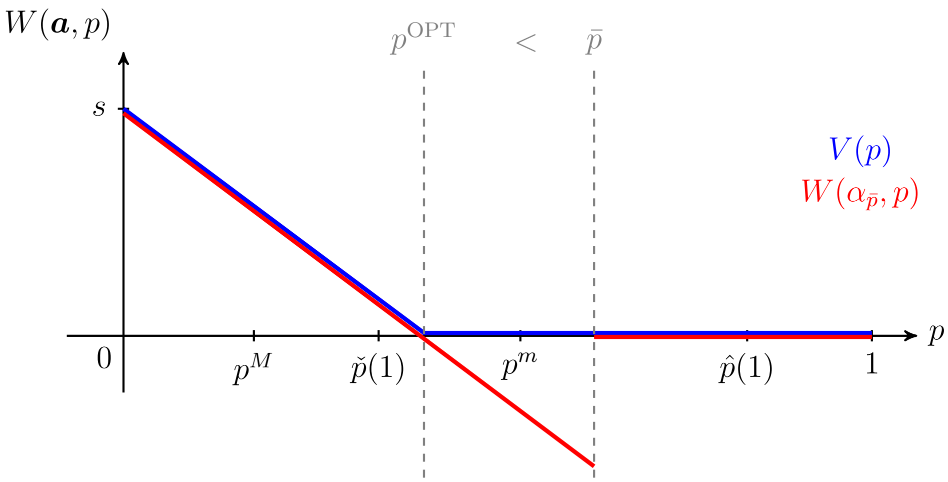

Figure 4: Equilibrium and Optimal Social Values with $\bar{p} > p^{\mathrm{OPT}}$.

These cases depend on the value of the social discount factor. For a fixed $\delta \in (0,1)$, there is one optimal threshold $p^{\mathrm{OPT}}(\delta)$, while there is a range of equilibrium thresholds in $\bar{P}(\delta)$. If $p^{\mathrm{OPT}}(\delta) \in \bar{P}(\delta)$, then there exists an optimal SMPE. If not, then equilibrium behavior and optimal behavior are necessarily in conflict. By comparing the threshold values, one can see that if δ is too low, then $p^{\mathrm{OPT}}(\delta) < \max\{p^{\dagger}, \check{p}(\delta)\}$. If δ is too high, then $p^{\mathrm{OPT}}(\delta) > \hat{p}(\delta)$. This means that an optimal SMPE exists for intermediate discount rates. This is stated in the following theorem.

Theorem 3. *There are $0 < \underline{\delta} < \overline{\delta} \leq 1$ such that an optimal SMPE exists if $\delta \in [\underline{\delta}, \overline{\delta}]$.*

Intuitively, when δ is low, temporal effects through the informational externality become muted and the payoff externality dominates. Both the planner and the generations are myopic—they care only about their immediate futures. However, the immediate future of each generation only involves themselves, while the immediate future of the planner also takes into account the previous generation. On the other hand, when δ is high, the informational externality dominates. Each generation only cares about their own lifetime—ignoring the future informational benefits of the risky technology—resulting in an inefficiently low use of the risky technology.

While one wishes that the generations would settle on the threshold that is closest to the optimal one, all SMPEs are equally focal in the current model. It would be interesting to ask how a near-optimal equilibrium could be favored. However, one can also argue that the myopic equilibrium with threshold p^m is most likely to occur since it survives as an equilibrium for all discount rates.

5 Political Equilibrium

This section relaxes the assumption that the young decide on experimentation. I first ask whether the old and the young can work together to achieve a better outcome than that of the baseline model. The answer is no—only under-experimentation arises. Some tension between the young and the old seems to be crucial for optimal experimentation. I then present a generalization with a political process whereby the young and the old vote on the choice of technology. I show that in this game the old should be given less than half of the political power.

5.1 Short-lived Planner

This section looks at a game between *short-lived planners*, where planner t represents the interests of the entire population at time t—that is, both the young and the old. Planner t's problem is to choose whether or not to experiment with the payoff:

$$(s - p_t\lambda 2)a_t - \delta(1 - p_t\lambda a_t)p_{t+1}\lambda a_{t+1}. \tag{16}$$

The difference from generation t's payoff previously in (6) is the extra 2 in the first term, which accounts for the risk faced by the old. Thus, for the purpose of equilibrium characterization the game with short-lived planners is strategically equivalent to the baseline game up to a reparameterization.

Proposition 1. *$\alpha_{\bar{p}}$ constitutes an SMPE of the game with short-lived planners if and only if*

$$\bar{p} \in \left[\max\left\{\check{p}\left(\frac{s}{2}, \frac{\delta}{2}\right), p^\dagger\left(\frac{s}{2}\right)\right\}, \hat{p}\left(\frac{s}{2}, \frac{\delta}{2}\right)\right], \tag{17}$$

All SMPEs exhibit under-experimentation.

The short-lived planner game models a situation where self-interest is not confined to within a generation, but within a period. Another interpretation is that the young and the old coordinate, perhaps through a political process, to choose whether or not to experiment at time t.

Does this get society any closer to optimal experimentation? Unfortunately not. Since $p^M < p^{\mathrm{OPT}}(\delta)$, only the preemptive equilibria (in this setting, this means the equilibria with threshold larger than p^M) of the short-lived planner game have any chance of being optimal. Cautious equilibria (those with threshold lower than p^M) are never optimal. However, it turns out that the preemptive equilibria are also not optimal as the short-lived planner is more conservative than the generation. Under-experimentation is guaranteed because $\hat{p}(s/2, \delta/2) < p^{\mathrm{OPT}}(\delta)$ for all $\delta > 0$.

How can correcting for an externality—by giving voice to the old who is negatively affected by the young's action—result in a worse outcome? The answer is that though this political process shuts off the payoff externality, which is the driving force of over-experimentation, it still lets the informational externality roam free. As will be shown next, one can do better by alleviating the payoff externality just enough to counter the informational externality, allowing for the possibility for optimal experimentation.

5.2 Political Process

The short-lived planner equilibrium is a special case of a *political equilibrium*, where a vote on the use of the risky technology takes place in every period. In the baseline model, the young are in total control of the decision and the old have no say. In the case of the short-lived planner, the young and the old have equal say. This section considers the intermediate case where period t's *political payoff*[21] is given by

$$\left(s - \frac{p_t\lambda}{\pi}\right) a_t - \delta(1 - p_t\lambda a_t)p_{t+1}\lambda a_{t+1}, \tag{18}$$

where $\pi \in [0, 1]$ is called a *political process*, interpreted as the young's relative political power. The baseline model has $\pi = 1$, in which the young have all the political power, while the short-lived planner case has $\pi = 1/2$, in which the political power is equally shared. Following Song et al. (2012)'s intergenerational model of public expenditure and debt, the political payoff and the parameter π can be micro-founded by a probabilistic voting model between the young and the old. As in the case of short-lived planners, the political equilibrium of the game with political process is characterized via a reparameterization of the baseline case.

Proposition 2. *$\alpha_{\bar{p}}$ constitutes an SMPE of the game with political process $\pi \in [0, 1]$ if*

[21] The expression is essentially a convex combination of the young and the old payoffs.

and only if
$$\bar{p} \in \left[\max\left\{\check{p}\left(\pi s, \pi\delta\right), p^{\dagger}\left(\pi s\right)\right\}, \hat{p}\left(\pi s, \pi\delta\right)\right]. \tag{19}$$
If $\pi \leq 1/2$, all SMPEs exhibit under-experimentation.

I have shown that for $\pi = 1$ (baseline case), an optimal equilibrium does not exist if $\delta \notin [\underline{\delta}, \overline{\delta}]$. For $\pi = 1/2$ (short-lived planner), an optimal equilibrium does not exist for any δ. When $\pi = 0$, the old have all the political power and they will never prescribe experimentation: $\bar{p} = 0$ is the only equilibrium threshold. Again, this means that an optimal equilibrium does not exist. Indeed, for any $\pi \leq 1/2$, there is no optimal equilibrium. Intuitively, giving too much political power to those who do not profit from using the risky technology results in under-experimentation and hinders society's potential to learn about new technologies.

However, an appropriately chosen political process (one with $\pi > 1/2$) can indeed improve upon the baseline model, but only to correct for over-experimentation. Modifying the result in Theorem 3 to allow for a political process gives the following.

Theorem 4. *If $\delta \in (0, \overline{\delta}]$, then there is an optimal SMPE in the intergenerational experimentation game with some political process $\pi^* \in (1/2, 1]$.*

To see why this holds, consider Theorem 3. When $\delta < \underline{\delta}$, all SMPEs have thresholds higher than the optimal threshold, so every SMPE exhibits over-experimentation. Recall that over-experimentation is the tendency to use the risky technology when it is not in society's best interest to do so. This resulted from the payoff externality—the young do not internalize the potential for catastrophic damage on the old. If we give some political power—through an appropriately chosen π—to the old, then this inefficiency can be corrected. One such π is given by:
$$\pi^* \equiv \frac{\delta\lambda + (1-\delta)}{\delta s + (1-\delta)2}. \tag{20}$$
To see this, note that $\pi s/\lambda$ is always in the set of equilibrium thresholds. Setting π^* such that $\pi s/\lambda = p^{\text{OPT}}(\delta)$ guarantees the existence of an equilibrium that mimics the optimal policy. However, π^* cannot always be chosen since the right-hand-side of (20) ranges from $1/2$ to $\lambda/s > 1$, while π^* cannot be more than 1. Indeed, it cannot correct for under-experimentation when the society is too patient, $\delta > \overline{\delta}$. This is intuitive since $\pi < 1$ means inviting the old to be included in the decision process and they do not support experimentation. If there is under-experimentation when $\pi = 1$, then there will be even more under-experimentation when $\pi < 1$.

6 Discussion and Extensions

I consider four alternative specifications to the baseline model. First, I consider the finite-horizon version of the game and demonstrate that only the myopic equilibrium survives. Second, I remove the payoff externality and show that without it only under-experimentation arises. Third, I investigate a model where damage from a catastrophe lasts for many periods. Lastly, I argue that the assumption of risk neutrality is without much loss of generality as risk aversion does not qualitatively change the results.

6.1 Finite-Horizon

As mentioned, when there is a definite end date to the game, the continuum of equilibria vanishes and only the myopic equilibrium survives. I now formally analyze the finite-horizon model.

Define a *truncated game* with end date $T < \infty$ as a finite-horizon game with T players who move sequentially one at a time and whose payoffs are

$$u_t(\boldsymbol{a}^T) = (s - p_t\lambda)a_t - \delta(1 - p_t\lambda a_t)p_{t+1}\lambda a_{t+1} \tag{21}$$

for $t \in \{0, \ldots, T-2\}$ and $u_{T-1}(\boldsymbol{a}^T) = (s - p_{T-1}\lambda)a_{T-1}$, where $\boldsymbol{a}^T = (a_0, \ldots a_{T-1}) \in \{0,1\}^T$. The equation of motion for the belief p_t is as before. We have the following proposition.

Proposition 3. *In a truncated game with any $T < \infty$, the unique MPE is $a_t = \alpha_{p^m}$.*

It turns out that the myopic equilibrium is indeed the unique MPE. There are no other MPEs, non-stationary, non-threshold, or otherwise. Moreover, the myopic equilibrium is also equivalent—in the sense that it prescribes the same behaviors and implements the same outcome for any starting belief—to the unique subgame perfect equilibrium (SPE) of the truncated finite-horizon game. This can be shown by a direct backward induction proof. This again indicates that the multiplicity of equilibria in the infinite-horizon game rests on a folk-theorem-type result. The truncated game equilibrium behavior is akin to the defection equilibrium of a finitely-repeated prisoner's dilemma, while the continuum of equilibria in Theorem 1 is akin to the multiplicity of SPEs in an infinitely-repeated prisoner's dilemma. Indeed, some of these strategies can—depending on the values of the discount rate as in Theorem 3—sustain optimal behavior, just like how the grim-trigger strategy can sustain a cooperation equilibrium in an infinitely-repeated prisoner's dilemma.

6.2 No Payoff Externality

I now look at a model without the payoff externality. The equilibrium behavior in a model without the payoff externality is simply the myopic threshold strategy because every generation compares their own private costs and benefits of experimentation. Now, optimal behavior solves the social planner's problem without the payoff externality:

$$\max_{\boldsymbol{a}} \mathbb{E}_p \left[(1-\delta) \sum_{t=0}^{\infty} \delta^t \chi_t \left(s - \mathbb{1}_{\{\omega=\mathcal{B}\}} \lambda \right) a_t \right]. \tag{22}$$

This problem is akin to a single-agent experimentation problem, where one compares the myopic solution with the optimal policy. I demonstrate the following proposition for the model with no payoff externality.

Proposition 4. *The unique SMPE of the game with no payoff externality is α_{p^m}. The optimal policy of the game with no payoff externality is α_{p^*}, where*

$$p^*(\delta) \equiv \frac{s}{\lambda} \frac{\delta\lambda + (1-\delta)}{\delta s + (1-\delta)}. \tag{23}$$

The SMPE exhibits under-experimentation.

As mentioned in Section 3, without the payoff externality preemptive behaviors disappear because the young know that the next generation will not be able to affect them when they are old. Because of this, equilibrium behavior does not exhibit over-experimentation (as compared to optimal behavior of the model without the payoff externality). Moreover, without the payoff externality, the informational externality actually has no bite: the beliefs of future generations do not affect the current generation's payoff in any way. Nevertheless, under-experimentation persists. This is due to the fact that generations are short-lived and do not want to pay present costs for the potential future benefits that would come from finding out that the true state is after all good.

6.3 Long-term Impact

Let us now consider a model where the impact of a catastrophe lasts for $\tau \geq 2$ periods. I call this game intergenerational experimentation with *long-term impact*. When $\tau = \infty$, the impact is *irreversible*.

Generation t's payoff is now

$$u_t = (s - p_t\lambda)a_t - \delta p_t \lambda a_t - \delta(1 - p_t\lambda a_t)p_{t+1}\lambda a_{t+1} \tag{24}$$

The difference from generation t's previous payoff, in (6), is the additional term in the middle. This term represents the damage in the next period that generation t incurs if a catastrophe happens. The planner's payoff is now

$$\mathbb{E}_p\left[(1-\delta)\sum_{t=0}^{\infty}\delta^t\chi_t\left(s-\mathbb{1}_{\{\omega=\mathcal{B}\}}\lambda 2X(\tau,\delta)\right)a_t\right], \tag{25}$$

where $X(\tau,\delta) \equiv 1+\delta+\delta^2+\cdots+\delta^{\tau-1}$. We have the following result.

Proposition 5. *$\alpha_{\bar{p}}$ constitutes an SMPE of the game with long-term impact ($\tau \geq 2$) if and only if*

$$\bar{p} \in \left[\max\left\{\check{p}\left(\frac{s}{1+\delta},\frac{\delta}{1+\delta}\right), p^{\dagger}\left(\frac{s}{1+\delta}\right)\right\}, \hat{p}\left(\frac{s}{1+\delta},\frac{\delta}{1+\delta}\right)\right]. \tag{26}$$

The optimal policy is α_{p^τ}, $\tau < \infty$, where

$$p^{\tau}(\delta) \equiv \frac{s}{\lambda}\frac{\delta\lambda+(1-\delta)}{\delta s+(1-\delta)2X(\tau,\delta)}. \tag{27}$$

If the impact is irreversible, the optimal policy is α_{p^∞}, where

$$p^{\infty}(\delta) \equiv \frac{s}{\lambda}\frac{\delta\lambda+(1-\delta)}{\delta s+2}. \tag{28}$$

In the case of long-term impact, it is not surprising that the social planner is more conservative—only prescribing experimentation when the initial belief is extremely optimistic, that is, when a catastrophe is likely impossible. But how do the generations behave? Proposition 5 asserts that there is still a continuum of equilibria for the intergenerational game. However, preemptive behaviors no longer arise, because for all $\delta \in (0,1)$,

$$p^m > \hat{p}\left(\frac{s}{1+\delta},\frac{\delta}{1+\delta}\right). \tag{29}$$

Recall that the intuition for preemption was that: "if you (the next generation) are going to sabotage the world, then I (the current generation) would rather do so now and get some of the benefits!" With long-term impact, this sentiment no longer holds since damage lasts for multiple periods: using the risky technology now will also cause a damage in the future.

6.4 Risk Aversion

The paper has thus far assumed that generations are risk-neutral. Suppose that each generation is an expected utility maximizer with a utility function $u(\cdot)$ which is strictly increasing and concave, $u'(\cdot) > 0$ and $u''(\cdot) < 0$, and normalized so that $u(0) = 0$. It turns out that risk aversion does not qualitatively alter the results, but simply transforms the parameters s and δ.

At time t, using the safe technology yields $u(0)$ to generation t. A risky technology, however, yields $(1-p_t)u(s)+p_t\left[(1-\lambda)u(s)+\lambda u(s-1)\right]$. The expected payoff at $t+1$, conditioning on no catastrophe, is either $(1-p_{t+1})u(0)+p_{t+1}\left[(1-\lambda)u(0)+\lambda u(-1)\right]$ or $u(0)$ depending on whether or not the young at $t+1$ use the risky technology. Together, generation t's payoff can be written as:

$$\left[u(s)-\left(u(s)-u(s-1)\right)p_t\lambda\right]a_t+\delta(1-p_t\lambda a_t)p_{t+1}\lambda u(-1)a_{t+1} \tag{30}$$

A strategically equivalent payoff is

$$\left[\frac{u(s)}{u(s)-u(s-1)}-p_t\lambda\right]a_t-\frac{|u(-1)|}{u(s)-u(s-1)}\delta(1-p_t\lambda a_t)p_{t+1}\lambda a_{t+1} \tag{31}$$

Note that the payoff in (31) has the same form as that in (6). Define

$$s^\sigma\equiv\frac{u(s)}{u(s)-u(s-1)}\qquad\text{and}\qquad\delta^\sigma\equiv\frac{|u(-1)|}{u(s)-u(s-1)}\delta \tag{32}$$

to be the effective benefits of the risky technology and the effective discount factor with risk aversion, respectively. With risk neutrality, $s^\sigma=s$ and $\delta^\sigma=\delta$ as expected. Now, by concavity of u, it is easy to see that $\delta^\sigma\geq\delta$ and more difficult to see that $s^\sigma\leq s$.[22] Thus, the same method of equilibrium characterization (Theorem 1), subject to the condition that $\delta^\sigma\leq 1$, also works when generations are risk-averse. It follows from this observation that risk-aversion effectively lowers the benefits of the risky technology, deterring its use, while at the same time enlarges the set of equilibria. The qualitative features of the set of equilibria do not change.

7 Conclusion

I study the problem of intergenerational tragedy of the commons via a model of strategic experimentation with overlapping generations. There is an equilibrium where the players' behaviors align with what would have been prescribed by a social planner. Importantly, this alignment rests on the discount rate. The existence of this optimal equilibrium, however, is not robust. I show that for many variations of the model, equilibrium behavior cannot be socially optimal.

Future research might attempt to find ways of enforcing the best equilibrium when one exists, perhaps through an intergenarational Pigouvian tax or other political process.

[22] This follows because $s\in(0,1)$ and

$$su(s-1)+(1-s)u(s)\leq u(s(s-1)+(1-s)s)=0.$$

Another direction is to relax the assumption of a homogeneous Poisson process, where the probability of a catastrophe in the bad state stays constant over time. This is challenging since one loses stationarity, but it promises to be a fruitful endeavor. Alas, many assumptions had to be made for the purpose of solvability and tractability. My hope is that this work adds to the literature by offering new ways to think about the problem of strategic experimentation in the context of intergenerational conflicts and catastrophes.

A Proofs

Proof of Lemma 1. These facts follow from elementary calculus and algebra. $\square$

Proof of Lemma 2. These facts follow from elementary calculus and algebra. $\square$

Proof of Theorem 1. The proof proceeds in three steps. First, I show that any SMPE is in threshold strategy, $\mathcal{A}^* \subset \bar{\mathcal{A}}$. Second, for $\bar{p} \in \bar{P}(\delta)$, I show that $a_t = \alpha_{\bar{p}}(p)$ is a best-response to $a_{t+1} = \alpha_{\bar{p}}(p')$ for any p. Third, I prove the only if part by showing that $\alpha_{\bar{p}}$ does not constitute an SMPE if $\bar{p} \notin \bar{P}(\delta)$.

Step 1. It suffices to show that a threshold strategy is a (generically) unique best-response to any strategy. Suppose the next generation uses $\tilde{\alpha} \in \mathcal{A}$ and that the current belief is p. The relevant actions of the next generation are $\tilde{\alpha}(p) \in \{0,1\}$ and $\tilde{\alpha}(p') \in \{0,1\}$, where $p' = \frac{p(1-\lambda)}{1-p\lambda}$. I now show that the best-response against each of the four possibilities is a threshold strategy.

(i) If $\tilde{\alpha}(p) = 0$ and $\tilde{\alpha}(p') = 0$, so the next generation takes the safe action regardless. Thus, the current generation should take the risky action if $s - p\lambda \geq 0$ or $p \leq s/\lambda$.

(ii) If $\tilde{\alpha}(p) = 1$ and $\tilde{\alpha}(p') = 1$, so the next generation takes the risky action regardless. Thus, the current generation should take the risky action if $(s - p\lambda) - \delta p(1-\lambda)\lambda \geq -\delta p\lambda$ or $p \leq \frac{s}{\lambda(1-\delta\lambda)}$.

(iii) If $\tilde{\alpha}(p) = 0$ and $\tilde{\alpha}(p') = 1$, so the next generation takes the risky action only if the current takes the risky action regardless. Thus, the current generation should take the risky action if $(s-p\lambda) - \delta p(1-\lambda)\lambda \geq 0$ or $p \leq \frac{s}{\lambda(1+\delta(1-\lambda))}$.

(iv) If $\tilde{\alpha}(p) = 1$ and $\tilde{\alpha}(p') = 0$, so the next generation takes the risky action only if the current takes the safe action. Thus, the current generation should take the risky action if $(s - p\lambda) \geq -\delta p\lambda$ or $p \leq \frac{s}{\lambda(1-\delta)}$.

These best-responses are unique up to prescription of the action exactly on the threshold, so it follows that all SMPEs are in threshold strategies.

Step 2. Fix $\bar{p} \in \bar{P}(\delta)$ and suppose that generation $t+1$ uses the threshold strategy $\alpha_{\bar{p}}$.

(i) If $p \leq \bar{p}$, then since p' is either p or $p(1-\lambda)/(1-p\lambda) \leq p$, we have that $p' \leq \bar{p}$. This means that $a_{t+1} = \alpha_{\bar{p}}(p') = 1$, so generation t's best-response is to choose $a_t = 1$ which maximizes

$$[s - p\lambda(1-\delta\lambda)]a_t - \delta p\lambda. \tag{33}$$

This holds because $p \leq \bar{p} \leq \hat{p}(\delta)$, so $s - p\lambda(1-\delta\lambda) \geq 0$. Thus, $a_t = \alpha_{\bar{p}}(p)$ is a best-response.

(ii) If $p > \bar{p}$, then p' can either be greater than or less than $\bar{p}$, depending on a_t and how much higher p is from $\bar{p}$. Suppose p is such that $p(1-\lambda)/(1-p\lambda) > \bar{p}$, so $p' > \bar{p}$ regardless. Then, $a_{t+1} = \alpha_{\bar{p}}(p') = 0$ always. Now, I claim that $p \geq p^m$, so that $s - p\lambda < 0$, and $a_t = 0$ is a best-response. Suppose not, then $p < p^m$ would imply that $p(1-\lambda)/(1-p\lambda) < p^\dagger$, a contradiction to $\bar{p} \in \bar{P}(\delta)$. On the other hand, suppose p is such that $p(1-\lambda)/(1-p\lambda) \leq \bar{p}$, then $a_t = 0$ means that $a_{t+1} = \alpha_{\bar{p}}(p') = 0$, while $a_t = 1$ would push p' down so that $a_{t+1} = \alpha_{\bar{p}}(p') = 1$. Generation t then effectively chooses between payoffs of 0 and $s - p\lambda[1+\delta(1-\lambda)]$. Now, because $p > \bar{p} \geq \hat{p}(\delta)$, we have $s - p\lambda[1+\delta(1-\lambda)] < 0$. Thus, in both cases, the best-response is to follow the threshold strategy, $a_t = \alpha_{\bar{p}}(p)$.

Step 3. Fix $\bar{p} \notin \bar{P}(\delta)$. There are three non-mutually exclusive, but exhaustive cases.

(i) $\bar{p} < \check{p}(\delta)$. Consider $p \in (\bar{p}, \check{p}(\delta))$, so $\alpha_{\bar{p}}(p) = 0$. This yields a payoff of 0 since $a_{t+1} = \alpha_{\bar{p}}(p') = 0$. Now, $a_t = 1$, would either mean $a_{t+1} = \alpha_{\bar{p}}(p') = 0$ or $a_{t+1} = \alpha_{\bar{p}}(p') = 1$. In either case, the payoff is strictly positive—a profitable deviation.

(ii) $\bar{p} < p^\dagger$. Consider $p = p^m - \epsilon$ for a sufficiently small $\epsilon > 0$ such that $p(1-\lambda)/(1-p\lambda) \in (\bar{p}, p^\dagger)$. Such an ϵ exists because the definition of $p^\dagger$ and the fact that $p \mapsto p(1-\lambda)/(1-p\lambda)$ is a continuous map. For such p, $\alpha_{\bar{p}}(p) = 0$, but $a_t = 1$ is a profitable deviation since it yields $s - p\lambda$, which is strictly positive for $p < p^m$.

(iii) $\bar{p} > \hat{p}(\delta)$. Consider $p \in (\hat{p}(\delta), \bar{p})$, so $\alpha_{\bar{p}}(p) = 1$. Then, $p' < \bar{p}$ always, meaning that $a_{t+1} = \alpha_{\bar{p}}(p') = 1$. A profitable deviation is to choose $a_t = 0$ since $s - p\lambda(1-\delta\lambda) < 0$ for $p > \hat{p}(\delta)$.

Thus, $\alpha_{\bar{p}}$ does not constitute an equilibrium for $\bar{p} \notin \bar{P}(\delta)$.

$\square$

Proof of Corollary 1. The corollary follows from the definition of $\bar{P}(\delta)$ in Theorem 1 and the properties of $\check{p}(\delta)$ and $\hat{p}(\delta)$ from Lemma 1. $\square$

Proof of Theorem 2. The value function can be rewritten out

$$V(p) = \max_{\boldsymbol{a}} \left\{ (1-\delta)(s - p\lambda 2)a_0 + \mathbb{E}_{p'} \left[(1-\delta) \sum_{t=1}^{\infty} \delta^t \chi_t (s - \mathbb{1}_{\{\omega=\mathcal{B}\}} \lambda 2) a_t \right] \right\}, \tag{34}$$

where $p' = p(1-\lambda a_0)/(1-p\lambda a_0)$. Now, conditioning on $\chi_1 = 1$, the event that the game has no ended by time 1, which occurs with probability $(1-p\lambda a)$, we can write the Bellman equation as

$$V(p) = \max_{a\in\{0,1\}} (1-\delta)(s-p\lambda 2)a + \delta(1-p\lambda a)V(p') \tag{35}$$

where $p' = p(1-\lambda a)/(1-p\lambda a)$.

First, note that $V(0) = s$ because $p = 0$ implies $p' = 0$, so the Bellman equation gives $V(0) = \max_{a\in\{0,1\}} (1-\delta)sa + \delta V(0)$. Now, for $p < 1$, the value function must satisfy

$$V(p) = \max\left\{\delta V(p), (1-\delta)(s-p\lambda 2) + \delta(1-p\lambda)V(p')\right\} \text{ where } p' = \frac{p(1-\lambda)}{1-p\lambda}. \tag{36}$$

Note that if $\delta V(p) \geq (1-\delta)(s-p\lambda 2) + \delta(1-p\lambda)V(p')$, then $V(p) = \delta V(p)$, which implies $V(p) = 0$ because $\delta < 1$. Therefore, we have that

$$V(p) = \max\left\{(1-\delta)(s-p\lambda 2) + \delta(1-p\lambda)V(p'), 0\right\}, \tag{37}$$

which can now iterate to solve for the closed-form expression of $V(p)$. Consider p such that $V(p) > 0$, then using $\rho(k,p) \equiv p(1-\lambda)^k + (1-p)$ as defined, we have

$$\begin{aligned}
V(p) &= (1-\delta)(s-p\lambda 2) + \delta\rho(1,p)V(p') \\
&= (1-\delta)(s-p\lambda 2) + \delta\rho(1,p)\left[(1-\delta)\left(s - \frac{p(1-\lambda)}{\rho(1,p)}\lambda 2\right) + \delta\frac{\rho(2,p)}{\rho(1,p)}V(p'')\right] \\
&= (1-\delta)\left\{(s-p\lambda 2) + \delta[s\rho(1,p) - p\lambda 2(1-\lambda)]\right\} + \delta^2\rho(2,p)V(p'') \\
&= (1-\delta)\{(s-p\lambda 2) + \delta[s\rho(1,p) - p\lambda 2(1-\lambda)] \\
&\qquad + \delta^2[s\rho(2,p) - p\lambda 2(1-\lambda)^2]\} + \delta^3\rho(3,p)V(p''') \\
&= (1-\delta)\sum_{k=0}^{\infty}\delta^k\Omega(k,p),
\end{aligned} \tag{38}$$

where

$$\Omega(k,p) \equiv s\rho(k,p) - 2p\lambda(1-\lambda)^k. \tag{39}$$

Summing the geometric series gives

$$V(p) = s - p\lambda \frac{\delta s + (1-\delta)2}{\delta\lambda + (1-\delta)} \tag{40}$$

when p is such that $V(p) > 0$. The value function for all p follows. In particular, $V(0) = s$, $V(1) = 0$, and $V'(p) \leq 0$. Note that to get the optimal policy, we simply find the belief p^{OPT} where the downward sloping part of $V(p)$ hits zero. □

Proof of Lemma 3. These facts follow from elementary calculus and algebra. □

Proof of Theorem 3. The proof is by comparison of the threshold values for different δ such that $p^{\text{OPT}}(\delta) \in \bar{P}(\delta)$. By Lemma 1,

$$\max\{\check{p}(\delta), p^{\dagger}\} < \hat{p}(\delta). \tag{41}$$

We prove the upper and the lower bounds separately.

Upper bound. There is no optimal SMPE if $p^{\text{OPT}}(\delta) > \hat{p}(\delta)$.

We compare the quantities $\lambda p^{\text{OPT}}(\delta)/s$ and $\lambda\hat{p}(\delta)/s$, and call them LHS and RHS, respectively. At $\delta = 0$, LHS is $1/2$, while RHS is 1. At $\delta = 1$, LHS $= \lambda/s$, while RHS $= 1/(1-\lambda)$. Now, because both quantities are strictly increasing in δ, there exists $\bar{\delta} \leq 1$ such that $p^{\text{OPT}}(\delta) \leq \hat{p}(\delta)$ for $\delta \leq \bar{\delta}$ and $p^{\text{OPT}}(\delta) > \hat{p}(\delta)$ otherwise. Note that $\bar{\delta}$ may be 1, which means that $p^{\text{OPT}}(\delta) \leq \hat{p}(\delta)$ for all δ. This occurs when $\lambda/s \leq 1/(1-\lambda)$. Furthermore, at $\bar{\delta}$, $p^m < p^{\text{OPT}}(\bar{\delta})$.

We can derive an explicit $\bar{\delta}$ by a direct comparison. This yields that

$$\bar{\delta} = \min\left\{ \frac{\sqrt{(1-s)^2 + 4(1-\lambda)\lambda} - (1-s)}{2(1-\lambda)\lambda}, 1 \right\}. \tag{42}$$

Lower bound. There is no optimal SMPE if $p^{\text{OPT}}(\delta) < \max\{\check{p}(\delta), p^{\dagger}\}$.

Either $p^{\dagger} \leq \check{p}(1)$, so $\max\{\check{p}(\delta), p^{\dagger}\} = \check{p}(\delta)$ for all δ or $p^{\dagger} \in (\check{p}(1), \check{p}(0))$. Define $\delta^{\dagger} \in (0,1]$ such that $\max\{\check{p}(\delta), p^{\dagger}\} = \check{p}(\delta)$ if and only if $\delta \leq \delta^{\dagger}$. At $\delta = 0$, $p^{\text{OPT}}(0) < \max\{\check{p}(0), p^{\dagger}\} = \check{p}(0) = p^m$. At $\delta = 1$, $p^{\text{OPT}}(1) > \max\{\check{p}(1), p^{\dagger}\} = \check{p}(\delta^{\dagger})$. Now, since p^{OPT} is strictly increasing and $\max\{\check{p}(\delta), p^{\dagger}\}$ is weakly decreasing, there must exists $\underline{\delta} > 0$, where they intersect. Such $\underline{\delta}$ must also satisfy $p^{\text{OPT}}(\underline{\delta}) < p^m$. Again, we can derive $\underline{\delta}$ explicitly:

$$\underline{\delta} = \max\left\{ \frac{(2-s) - \sqrt{(2-s)^2 - 4(1-\lambda)^2}}{2(1-\lambda)^2}, \frac{1+s-2\lambda}{1-\lambda} \right\}. \tag{43}$$

Together, we know that $\underline{\delta} < \bar{\delta}$ because $p^{\text{OPT}}(\underline{\delta}) < p^m < p^{\text{OPT}}(\bar{\delta})$.

If $\delta = \frac{1}{1+(\lambda - s)}$, then $p^{\mathrm{OPT}}(\delta) = p^m$. Since threshold p^m is always an equilibrium, there is always an optimal equilibrium at such discount rate. $\square$

Proof of Proposition 1. Rewrite planner t's utility as

$$2\left[\left(\frac{s}{2} - p_t\lambda\right) a_t - \frac{\delta}{2}(1 - p_t\lambda a_t)p_{t+1}\lambda a_{t+1}\right] \tag{44}$$

Thus, the strategic problem between short-lived planners is akin to generation t's problem with the parameters $s/2$ and $\delta/2$. The characterization is then a corollary of Theorem 1. Under-experimentation always ensues (unless $\delta = 0$) because the highest experimentation equilibrium threshold $\hat{p}\left(\frac{s}{2}, \frac{\delta}{2}\right)$ is lower than $p^{\mathrm{OPT}}(\delta)$. One can show that if $\delta > 0$, $\hat{p}\left(\frac{s}{2}, \frac{\delta}{2}\right) < p^{\mathrm{OPT}}(\delta)$ simplifies to $s < \lambda + \delta\lambda(1-\lambda)$, which holds. $\square$

Proof of Proposition 2. As with the short-lived planner problem, the characterization of the political equilibrium is a corollary of Theorem 1 with benefits and discount rate redefined to πs and $\pi\delta$, respectively. If $\pi \leq 1/2$, then $\hat{p}(\pi s, \pi\delta) \leq \hat{p}(s/2, \delta/2)$ and it follows from the proof of Proposition 1 that there is no optimal SMPE. $\square$

Proof of Theorem 4. This is essentially Theorem 3 modified with the reasoning in the main text. $\square$

Proof of Proposition 3. We first show that in the infinite-horizon game, for any $\bar{p} \in \bar{P}(\delta)$, $a_t = \alpha_{\bar{p}}$ is the unique best-response to $a_{t+1} = \alpha_{\bar{p}}$. Let $\alpha_{\bar{\bar{p}}}$ be another threshold strategy.

If $\bar{\bar{p}} < \bar{p}$, then consider $p \in (\bar{\bar{p}}, \bar{p})$. In this case, $p' < \bar{p}$, so $a_{t+1} = 1$. However, $\alpha_{\bar{\bar{p}}}(p) = 0$ and a profitable deviation is $a_t = 1$ since

$$(s - p\lambda) - \delta(1-\lambda)p\lambda = s - p\lambda(1 - \delta\lambda) - \delta p\lambda > -\delta p\lambda. \tag{45}$$

The inequality follows because $p < \bar{p} \leq \frac{s}{\lambda(1-\delta\lambda)}$.

If $\bar{\bar{p}} > \bar{p}$, then first let $\bar{\bar{p}} = \bar{p} + \epsilon$ for some $\epsilon > 0$ small enough. Consider $p \in (\bar{p}, \bar{\bar{p}})$. Since p is very close to $\bar{p}$, following the strategy $a_t = \alpha_{\bar{\bar{p}}}(p) = 1$ means that $a_{t+1} = \alpha_{\bar{p}}(p') = 1$ as well, while if $a_t = 0$, then $a_{t+1} = \alpha_{\bar{p}}(p') = \alpha_{\bar{p}}(p) = 0$. The former action yields a negative payoff, while the later gives zero. Thus, $a_t = 0$ is a profitable deviation and $\alpha_{\bar{\bar{p}}}$ is not a best-response. Now, suppose that $\bar{\bar{p}}$ is far enough away from $\bar{p}$, so there is a $p \in (\bar{p}, \bar{\bar{p}})$ such that $p(1-\lambda)/(1-p\lambda) > \bar{p}$. If this is the case, then $a_{t+1} = 0$ regardless of a_t and it follows that $\alpha_{\bar{\bar{p}}}(p) = 1$ is not a best-response.

We have established that for any t, $\alpha_{\bar{p}}$ is the unique best-response to $a_{t+1} = \alpha_{\bar{p}}$. In the truncated game, the last young generation at time $T-1$ chooses $a_{T-1} = \alpha_{p^m}$. It now follows that the unique best-response for a_{T-2} is also α_{p^m}. We can then work backwards to claim that in the truncated game, the only MPE is $a_t = \alpha_{p^m}$ for all $t \in \{0, 1, \ldots, T-1\}$. $\square$

Proof of Proposition 4. That equilibrium is $a_t = \alpha_{p^m}$ is straightforward. For the optimal policy, the proof is the same as that of Theorem 2 without the factor of 2. Since $\lambda > s$, $p^m \leq p^*(\delta)$ with equality if and only if $\delta = 0$, so there is under-experimentation if $\delta > 0$. □

Proof of Proposition 5. The proof of the equilibrium characterization is via redefining the appropriate parameters in Theorem 1. Specifically, write the payoff as

$$\begin{aligned} &a_t - \delta(1 - p_t\lambda a_t)p_{t+1}\lambda a_{t+1} \\ &\quad = (1+\delta)\left[\left(\frac{s}{1+\delta} - p_t\lambda\right)a_t - \frac{\delta}{1+\delta}(1 - p_t\lambda a_t)p_{t+1}\lambda a_{t+1}\right] \end{aligned} \tag{46}$$

Then redefine $s \mapsto s/(1+\delta)$ and $\delta \mapsto \delta/(1+\delta)$, and use the characterization from Theorem 1. For the planner's problem, redefining $2 \mapsto 2X(\tau, \delta)$ and derive the optimal policy from Theorem 2. □

B Two-Period Model

In the two-period model, time ends after generation 1 makes a decision. I allow the fragility parameter λ_t to be changing over time. I call the generations $G0$ and $G1$, and denote λ_0 and λ_1 to be their fragilities, respectively. Usage of the risky technology is also allowed to be a continuum, $a_t \in [0, 1]$.

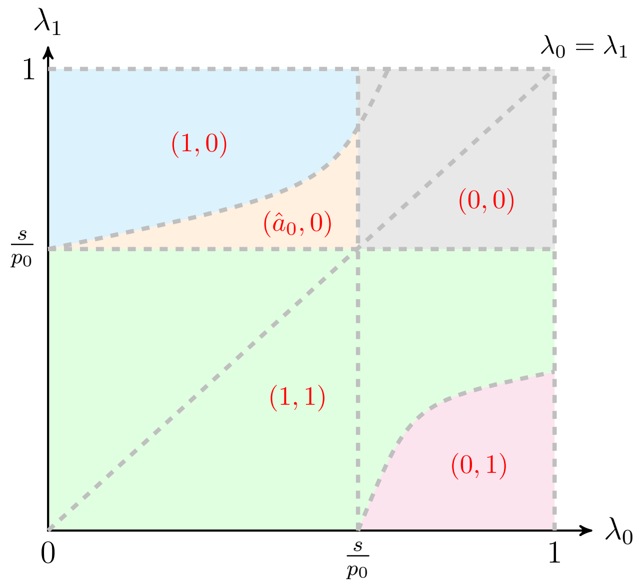

Figure 5: Equilibrium Outcomes for a Two-Period Model.

Assume for simplicity that $\delta = 1$. Generation 1, condition on no catastrophe, solves $\max_{a_1 \in [0,1]} sa_1 - p_1\lambda_1 a_1$, where $p_1 \equiv p_1(a_0; \lambda_0) = \frac{p_0(1-\lambda_0 a_0)}{1-p_0\lambda_0 a_0}$. If $s > p_0\lambda_1$ then $G1$ chooses

1 always because $p_1 \leq p_0$, i.e., if a breakdown does not occur, then a bad state is less likely. $G0$ solves

$$\max_{a_0 \in [0,1]} s a_0 - p_0 \lambda_0 a_0 - (1 - p_0 \lambda_0 a_0) p_1 \lambda_1. \tag{47}$$

This simplifies to $\max_{a \in [0,1]} [s - p_0 \lambda_0 (1 - \lambda_1)] a - p_0 \lambda_1$. Thus, if $s > p_0 \lambda_0$, then $s \geq p_0 \lambda_0 (1 - \lambda_1)$ and $G0$ chooses 1. If $s < p_0 \lambda_0$, then depending on the sign of $s - p_0 \lambda_0 (1 - \lambda_1)$ $G0$ chooses 0 or 1 (or a continuum in between). The most interesting case is when $p_0 \lambda_0 > s > p_0 \lambda_0 (1 - \lambda_1)$. This is when $G0$ will not experiment if they were by themselves. This is exactly the preemption incentive in the main model. However, when there is a possibility that $G1$ will cause the catastrophe, $G0$ at least wants some benefits to counter that breakdown cost. This is what I called the preemptive behavior in the full model.

Continuing with the analysis, if $s < p_0 \lambda_1$, then $G1$ chooses 0 or 1 (or the continuum in between) depending on the sign of $s - p_1 \lambda_1$. If $s > p_0 \lambda_0$, then the outcome is $(\max\{\hat{a}_0, 1\}, 0)$, where $\hat{a}_0$ is defined as a cutoff in $G0$'s action such that $G1$ is indifferent between experimenting and not. This reflects the cautious behavior in the full model, where the earlier generation is reluctant to experiment, even though it is beneficial in the myopic sense, since it will potentially invite more experimentation in the future. Lastly, if $s < p_0 \lambda_0$, then $(0, 0)$ occurs.

To summarize, we have:

(i) If $s > p_0 \lambda_1$ and $s > p_0 \lambda_0$, then equilibrium is $(1, 1)$.

(ii) If $s > p_0 \lambda_1$ and $s < p_0 \lambda_0$, then equilibrium is either $(0, 1)$ or $(1, 1)$.

(iii) If $s < p_0 \lambda_1$ and $s > p_0 \lambda_0$, then equilibrium is $(\max\{\hat{a}_0, 1\}, 0)$.

(iv) If $s < p_0 \lambda_1$ and $s < p_0 \lambda_0$, then equilibrium is $(0, 0)$.

The characterization is depicted in the λ-space in Figure 5. The bad news model, although can be thought of as a reverse of the good news model, yields simpler and qualitatively different—not just the opposite—results that that of the good news model.

In the main model of this paper, I have assumed that $\lambda_t = \lambda$ for all t. This translates to $\lambda_0 = \lambda_1 = \lambda$ in the two-period model. This case is captured by the diagonal of Figure 5. Only two outcomes prevail: $(1, 1)$ and $(0, 0)$. Either both generations experiment, given the chance, or no one experiments, just like the full indefinite-horizon model. In terms of MPE, the unique one here is the myopic threshold equilibrium, $p^m = s/\lambda$. As mentioned at the end of Section 3, this is the only MPE that prevails if the game ends at a fixed time. Off the diagonal, however, other interesting behaviors are possible. These behaviors are expected to be present if we relax the assumption on constant fragility in the full model.

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