Research Races: Innovation Policy and Technological Change

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This version: May 4, 2026

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R&D subsidies are widely used to foster innovation. Though effective, they require large fiscal outlays. In a model of competitive research, we show that high patent fees can be effective in encouraging firms to focus on disruptive innovations, providing an alternative policy tool. While high fees reduce the payoff from innovating, they encourage firms to focus on large-payoff projects and prevent unbundling of innovations, encouraging to continue development. Additionally, our model provides a simple supply-side explanation for people's growing mistrust in media: lower sharing costs push firms toward repeatable stories and swift publishing, with less fact-checking and potentially incomplete coverage.

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1 Introduction

Technological progress is a central driver of long-run economic growth, a principle formalized by Solow (1956) and later incorporated into endogenous growth theory by Romer (1990). Since ideas are inherently non-rival, private incentives to invest in innovation may fall short, making innovation policy essential. Broadly speaking, such policy operates through two sets of instruments: those that affect the degree of appropriability of ideas and those that reduce the private cost of research. The former include legal frameworks, enforcement, and the institutional features of patent systems, while the latter encompass R&D subsidies, tax credits, grants, and related fiscal tools that lower the cost of technological development.

Governments devote substantial resources to these policies. Across OECD countries, tax incentives and direct subsidies for business R&D amount on average to roughly 0.2% of GDP, reaching about 0.4% in countries such as Iceland, Portugal, and France (OECD (2024)). These magnitudes represent non-trivial fiscal commitments, particularly in economies facing persistent fiscal deficits and mounting demographic pressures on public finances. In this context, policy instruments that can influence innovation incentives without requiring comparable fiscal outlays are considerably valuable for policymakers.

In this paper, we propose bureaucratic implementation costs (e.g., patent fees and clinical trials) as a low-cost tool to shape private innovation incentives. High fees have a first-order effect of discouraging investment. However, they incentivize firms to pursue complex multi-stage innovations and progress further in these projects.[1]

We develop a dynamic model of innovation in which two firms compete to release a "radical" innovation, which requires multiple breakthroughs and represents large-payoff innovations creating new markets or technological directions. Alternatively, firms can choose to work on "incremental" innovations, which require one breakthrough and give a lower payoff, representing building on their own existing products or technologies absent competition. Crucially, firms may choose to "implement" or take to the market intermediate discoveries at any stage of development. Implementation entails paying a fixed cost that captures the broad set of expenditures required

[1]Empirical work arguing that patenting fees meaningfully affect firms' patenting decisions include classic work on renewal behavior (Pakes (1984)) and more recent evidence on patent applications (Rassenfosse and Potterie (2012)).

to commercialize new technologies, including marketing campaigns, reorganization of production and distribution networks, patenting procedures, and regulatory approval.

We show that implementation costs play a central role in shaping equilibrium innovation races. The effects are felt both in terms of the types of research firms choose to pursue, and also how intensely they do. Initial intuition suggests that lowering implementation costs will have two effects: it will encourage firms to focus on incremental innovations which have shorter development paths and will encourage firms to increase their investment.

The more nuanced effect of lower implementation costs is only seen through firms' interactions. Low implementation costs encourage firms to implement radical innovations at intermediate stages of development in order to preempt competitors. While early implementation creates a valuable information externality for competitors who can catch-up in the development race, it discourages the firm to keep researching relative to secrecy. This leads to halting research of the radical innovation if the private value of late-stages of development is low enough, and has ambiguous effects on how intensely firms pursue competitive projects.

We use the model to evaluate two widely used policy instruments: research subsidies and patenting fees. We show that lower research costs incentivize firms to work on multi-stage innovations and to avoid early implementation: at the margin, increasing research efforts becomes a better tool to protect proprietary knowledge relative to early patenting. Hence, R&D subsidies are an effective tool to promote firm investment and focus on radical innovations. However, we argue that higher patent fees can achieve part of this as well, by incentivizing firms to work on radical innovations and prevent patenting of intermediate stages, which lowers the incentive to keep investing in development.

We study optimal policy from the perspective of a planner seeking to minimize the expected time required to complete radical innovations. When the overall payoff from radical innovation is sufficiently large, the planner prefers low patent fees to maximize investment and exploit information spillovers from early disclosure. In contrast, when late stages of development yield relatively low private returns, positive patent fees are desirable to prevent premature disclosure and research abandonment. Likewise, positive patent fees are required to prevent firms from focusing on incremental innovation if payoffs from radical innovation are low enough. Moreover, patent fees and research subsidies act as partial substitutes: lower research costs strengthen incentives to pursue radical innovation and delay disclosure, reducing the level of fees required to sustain research effort over the full innovation path.

Beyond policy design, the framework provides a lens through which to interpret how technological change itself reshapes innovation incentives. We illustrate this with an application to the media industry. This industry has undergone a dramatic transformation in recent decades with daily newspaper cycles having been replaced by continuous digital updates. This shift has been accompanied by widespread concern about declining information quality and the rise of misinformation. While existing work emphasizes bias, persuasion, and demand-side forces, we offer a complementary supply-side explanation.

A key technological change – the sharp decline in publication costs brought about by digitalization – fits squarely within the mechanisms of our model. A drastic decline in publishing (implementation) costs in our model tilts incentives towards the release of preliminary information and away from high-value and deeply researched stories. Intuitively, firms release information as soon as possible to preempt competitors, resulting in less fact-checking and incomplete reporting. Importantly, this shift cannot be explained with an arguably possible decrease in research costs (e.g. AI, communication tools, etc.).

We take a next step and extend the model to argue that lower publication costs also increase the entry of copiers that erode profits of information producers, further incentivizing them to abandon high-value stories.

The model therefore provides a natural lens through which to interpret both the increase in publication frequency and the shift away from in-depth reporting toward simpler and less fact-cheking.

Related Literature. This paper contributes to the literature on innovation policy. An empirical literature studies whether R&D subsidies and tax incentives increase private innovative effort, with the main focus on the intensive margin of innovation, namely total R&D expenditure and patenting activity (Bloom, Griffith, and Van Reenen (2002), Dechezleprêtre et al. (2016), and Atkeson and Burstein (2019)). A related literature studies patent-system design, including patent scope, fees, renewal rules, and disclosure requirements, and how these affect firms' incentives to innovate and patent (Pakes (1984), Rassenfosse and Potterie (2012), Hopenhayn and Squintani (2016), Hegde, Ljungqvist, and Raj (2022), and Hegde, Herkenhoff, and Zhu (2023)). The closest paper to ours is Hopenhayn and Squintani (2016), which proposes a model in which firms' early patenting halts research progress and find that weaker patent rights may increase welfare through reduced competition that encourages firms to postpone patenting and continue product development further. We contribute to this line of work proposing a theory of how R&D subsidies and patent fees shape the level of innovative effort as well as on the direction and staging of innovation: whether firms pursue incremental or radical projects, whether they patent intermediate discoveries, and how much they continue investing in later stages of development. In this sense, our paper is also related models of radical and incremental innovation (Bryan and Lemus (2017) and Acemoglu, Akcigit, and Celik (2022)) such as Acemoglu, Akcigit, and Celik (2022)). Acemoglu, Akcigit, and Celik (2022) study how the age of managers affect firms' willingness to engage in radical innovations, finding a small but positive causal effect of manager age on creative innovations. More related to our paper, Bryan and Lemus (2017) study how innovation policies affect the direction of research and discuss optimal policy. We add patent fees to the discussion as a policy tool that can be used to direct innovation efforts where desired, pushing firms towards deeper research.

Second, the paper contributes to the theoretical literature on research races and the impacts of policy on disclosure. Early works include Loury (1979) in the research race setting, and Scotchmer and Green (1990) on disclosure in innovation. The main focus of this literature in recent years has been on the disclosure of intermediate results. Most related is Chatterjee et al. (2026), which studies how firm incentives to disclose intermediate stages of research shape the speed of multi-stage research races. They find that an increase in the final value of the research race only decreases the time to completion if the value is low. Both Kim and Tomaino (2026) and Kim and Poggi (2025) study when firms strategically share/conceal information in a research race. Our main contribution to this literature is three-fold. Technically we allow for non-linear costs of research that induce interactions between firm efforts and allow for an endogenous option that influences the race. These effects create new interactions in when firms decide to conceal or reveal information. We also connect this literature to the patenting literature by focusing on the policy implications of implementation costs.

Third, the paper contributes to a literature that studies information production in the media industry, most of which focuses on media slant (Gentzkow and Shapiro (2006) and Gentzkow and Shapiro (2010)), where firms have incentives to bias reporting to their own needs and the public's preferences, while part of it studies copying and misinformation (Allcott and Gentzkow (2017), Allcott, Gentzkow, and Yu (2019), and Cagé, Hervé, and Viaud (2020)). This literature explains mistrust in media as a result of bias. Our paper contributes by providing a technological supply-side explanation to a decline in news quality (and hence people's mistrust in media).

Lastly, we also contribute to a mostly empirical literature that studies the impact of new technologies on this industry (Gentzkow (2007), Franceschelli (2011), Salami and Seamans (2014), Jeon and Nasr (2016), Bisceglia (2023), and Bhuller et al. (2024)). Most of this literature focuses on how online media affected firm profits and the quality of newspaper content. A notable exception is Bisceglia (2023), who argues that the change from bundled stories in newspapers to individually published stories online results in a reduction of quality. Instead, we argue that a reduction in quality can come from lower publication costs which lead firms to focus on simple stories and publish complex ones at intermediate stages of development, with less fact-checking and verification.

Outline. Section 2 describes the main model and equilibrium behavior. Section 3 characterizes the equilibrium of the research race. Section 4 focuses on policy, discussing the role of R&D subsidies and patent fees in shaping innovation. Section 5 focuses on how technological progress shape the future innovation path, focusing on the news media industry. Finally, Section 6 concludes.

2 Model

There are two firms $i \in \{A, B\}$ competing to produce innovations in continuous time $t \in [0, \infty)$. There are two types of innovations: a "radical" competitive innovation R, and an "incremental" innovation I. These two innovation types capture qualitatively different research paths. Incremental innovations correspond to improvements that build directly on existing products or technologies, generate relatively modest payoffs, and typically face little direct competition. Radical innovations, by contrast, involve the pursuit of new technological directions or markets, promise large payoffs, and are often pursued simultaneously by multiple firms. As a result, radical innovations require longer development paths and give rise to strategic competition.

At each moment in time, firms choose (i) how much to invest in discovering innovations $\lambda \in \mathbb{R}_+$; (ii) what proportion of their investment is focused on the radical innovation $e \in [0, 1]$ (the complementary proportion $1-e$ is focused on the incremental innovation); and (iii) whether to implement the current innovations that they have discovered $p \in \{0, 1\}$. Accordingly, at each moment in time, firm i's action set is given by $\mathcal{A}_i = \mathbb{R}_+ \times [0, 1] \times \{0, 1\}$. [2]

When firm i invests $e\lambda$ total effort in an innovation in period of time $[t, t + dt)$, with probability $e\lambda dt$ the firm achieves a "breakthrough". Incremental innovations require only one breakthrough to be completed, while the radical innovation requires two breakthroughs obtained sequentially. Firms must be exposed to the first stage of the radical innovation before pursuing the second stage. This exposure can occur when they achieve a breakthrough on the first stage, or when their opponent implements the breakthrough, making it public information. We assume that incremental innovations are repeatable and firm-specific, implying that they are not competitive. By contrast, the radical innovation path is assumed to be unique: each stage may only be implemented by one firm, and only once.

When a firm chooses to implement its breakthrough(s), it captures additional profits, which we model as immediate gains.[3] When it implements an incremental innovation, it receives v_I. Since there are multiple breakthroughs that comprise a radical innovation, each may be implemented separately if valuable on its own. If a firm is the first to implement the first breakthrough of this competitive innovation, it receives v_1, and if it is the first to implement the second breakthrough it receives v_2. If firm i has achieved both breakthroughs of the competitive innovation and neither has previously been implemented, then the firm may implement the two together. If

[2] The model and results do not change if we allow firms to implement breakthroughs at a stochastic rate $p \in [0, \infty]$.

[3] We can think of this as the private value of a patent, which allows a firm to increase its future profits, or the market value obtained from selling it.

it does so, it receives $v_1 + v_2$.

To fix ideas, it is useful to contrast incremental and radical innovations through a concrete example. Incremental innovations correspond to single-step improvements that generate a consistent payoff v_I on their own. In the pharmaceutical industry, examples include reformulating an existing drug to reduce side effects, extending its duration of action, or improving its method of delivery (e.g., moving from injections to oral tablets). These innovations are valuable in isolation and require solving relatively self-contained problems.

Radical innovations, by contrast, involve the creation of fundamentally new products or capabilities and typically require solving multiple distinct problems before they become commercially viable. The development of a new drug illustrates this case. Firms must first identify a biological mechanism or target associated with a disease. Conditional on this discovery, they must then develop a compound that effectively interacts with that target. Only after these steps can firms address downstream challenges such as reducing costs, ensuring safety, scaling production, and obtaining regulatory approval. Progress at later stages is not meaningful without success in earlier ones, and while intermediate breakthroughs may have standalone value, completing the full sequence is required to obtain the final product.

Importantly, implementing a new innovation is costly to firms. Taking a product to the market generally requires incurring costs related to reorganizing production and distribution, conducting marketing campaigns, securing patent protection, and, in some industries, obtaining regulatory approval. We model these as fixed costs which are independent of the type of innovation being implemented: firms must also pay $c_p \leq v_I$ whenever they choose to implement a new innovation.[4] It can immediately be seen that this implementation cost provides an incentive to delay the implementation of the multi-stage radical innovation until they have achieved both breakthroughs.

In addition to implementation costs, investment in research is itself costly. Firms incur a flow cost $\alpha C(\lambda)$ per unit of time if they choose to invest λ in researching,

[4] Abstracting from patent filing and prosecution, other regulatory burdens affect implementation costs substantially. In pharmaceuticals, clinical trials alone involve large fixed expenditures: Moore et al. (2018) estimate a median cost of \$19 for pivotal trials supporting FDA approvals of new therapeutic agents between 2015 and 2016, with some trials costing more than \$300 million. Commercialization costs are also substantial: Schwartz and Woloshin (2019) report that medical marketing spending in the United States was about \$30 billion in 2016.

where α acts as the parameter controlling the level of research costs. They also discount the future at rate $r > 0$. We place the following assumption on the cost of investment.

Assumption 1. $C : \mathbb{R}_+ \to \mathbb{R}_+$ is strictly convex, with $C''' \geq 0$, and $C'(0) = 0$.

Information Structure. The baseline model assumes complete information, so firms observe each other's breakthroughs and research focus. This keeps the model tractable, helping isolate the main mechanisms. However, knowledge of an opponents' breakthroughs does not equal exposure: a lagging firm cannot skip first-stage development unless the leader implements its breakthrough. In this sense, while competitors observe the occurrence of a breakthrough, its underlying content, which enables work on the second stage, becomes public only upon implementation.

Note on Timing. If a firm achieves a breakthrough at time t, it may immediately implement the breakthrough at time t.[5] For the competitive innovation, it is possible that when firm i achieves a breakthrough at time t, firm j has already achieved the same breakthrough but has chosen to delay implementation. In this case, we assume that firm i has first right to implement the breakthrough at time t. This assumption reflects the idea that if firm i could hide its breakthrough for a small period of time dt, then it would be able to implement its breakthrough before firm j discovers that they have made a breakthrough and has time to respond.

2.1 Solution Concept

A (pure) strategy for firms $S_i : \mathcal{H} \to \mathcal{A}_i$ is a function mapping histories $h \in \mathcal{H}$ to actions $a_i \in \mathcal{A}_i$. Alternatively, we can think of a firm's choice of strategy as a choice of a measurable path a_i^t of investment, focus, and implementation decisions. Here, measurability is with respect to histories, which are defined by the filtration generated by breakthroughs and publications by both firms. Firms choose their strategy to maximize

$$\mathbb{E}\left[\int_0^\infty e^{-rt}\left[(v - c_p) \cdot \mathbb{1}\{\text{Implement innovation of value } v \text{ at } t\} - \alpha C(\lambda_t)\right] dt\right].$$

[5]Notice that since λ_i^t will be finite, simultaneous breakthroughs happen with zero probability.

We restrict attention to Markov strategies, in order to isolate the impact of innovation progress on firms' incentives. That is, we restrict attention to strategies S_i where the only dependence on the history h appears through the state of research for the competitive innovation. Since incremental innovations can be repeated, progress on incremental innovations does not alter firms' incentives. Hence firms' optimal decisions are independent of the number of incremental innovations that have been implemented (and by whom). We denote the state space Ω. There are six relevant states for firms ($|\Omega| = 6$):

1. b_n: neither firm has achieved any breakthroughs for the competitive innovation.
2. b_A: firm A has achieved a breakthrough, firm B hasn't.
3. b_B: firm B has achieved a breakthrough, firm A hasn't.
4. $b_{A,B}$: both firms have achieved a breakthrough.
5. p_1: the first breakthrough of the deep story has been implemented.
6. p_2: both parts of the deep story have been implemented.

We also focus on symmetric strategies. By this we mean, in all states apart from b_A, b_B—symmetric states—firms' choose the same investment levels, and choose the same focus and implementation decisions. Also, firms A's choices in state b_A, b_B match B's in state b_B, b_A. While we prove below that for all reasonable parameter values the only Markov equilibria are symmetric, assuming it at this stage eases the exposition.

Discussion of Model. Our model captures settings where firms decide both how much to invest in innovating, and what innovations to pursue. Incremental innovations in this context reflect small, iterative product improvements that firms frequently introduce. They are repeatable in the sense that there are many possible directions in which firms can improve existing products. The deep innovation reflects a possible new market, in which firms vie to be the lead producer of a new product. In these markets, firms' innovations are necessarily exclusionary: one firm introducing a new product line captures surplus that another firm cannot capture. The multiple stages of radical innovations reflect that establishing new markets requires being disruptive and solving complex problems. Implementing intermediate breakthroughs captures surplus, for example through patenting and licensing, but also leaves room for competitors to build on the underlying idea or technology and introduce the new product themselves.

As noted, a major assumption in the model is that firms observe the other's breakthroughs. In practice, while firms may be able to imperfectly observe competitors' progress on innovations, it is also possible for firms to hide progress in order to gain a competitive advantage.[6] We explore a variant of the model where firms' breakthroughs are hidden in Appendix B. Importantly, our major qualitative results extend to that setting.

3 Equilibrium Characterization

Given that this is a complete information game with a finite number of states, it is conceptually straightforward to solve via backward induction. At each state $\omega \in \Omega$, firms choose whether to implement their existing breakthroughs, how much to invest in research, and how much focus to place on the radical innovation. These choices depend on the firms' anticipated value from achieving a breakthrough, and from their anticipated value after their opponent achieves a breakthrough.

Theorem 1. *There is a unique Markov Perfect Competitive equilibrium that is symmetric and stable. If r is sufficiently small, this is the only stable equilibrium.*

In the rest of this section, we show how the equilibrium is found, and describe its properties. As the race progresses, firms' future values become simpler to determine, simplifying analysis. Consider the state $\omega = p_2$, where the radical innovation has been completed and implemented. In state p_2, firms' decisions are non-strategic: since the incremental innovation is repeatable, firm B's investment choices do not affect firm A's incentives. Moreover, since the radical innovation has been fully implemented, this state is absorbing. To see these, let $V_i(\omega)$ denote firm i's value function in state ω. In state $\omega = p_2$, the firm's only choice is their level of investment λ: there is no radical innovation on which to work, and implementation decisions are trivial (it will always implement the incremental innovation immediately upon a breakthrough).

[6] This has been a focus of much recent work on research races. See, for instance, Chatterjee et al. (2026).

For dt small, it is possible to write $V_i(p_2)$ as the solution to

$$V_i(p_2) = \max_{\lambda_i} \left\{ \lambda_i \left(v_I - c_p \right) \cdot dt + (1 - r \cdot dt) \, V_i(p_2) - \alpha C(\lambda_i) \cdot dt \right\}$$

Rewriting this yields

$$V_i(p_2) = \max_{\lambda_i} \frac{\lambda_i (v_I - c_p) - \alpha C(\lambda_i)}{r}$$

This allows for a straightforward characterization of the optimal investment $\lambda^*(p_2) = \lambda_i^*(p_2)$ and $V(p_2) = V_i(p_2)$. Equipped with $V(p_2)$, it is possible to solve for preceding states. Formal derivations, as well as all proofs, are in the Appendix. As an example, consider firms' behaviour in state $\omega = b_{A,B}$. Suppose that both firms choose to delay implementation in state $b_{A,B}$, and also choose to work solely on the radical innovation (i.e. $e_i = 1$ for both $i = A, B$). Denote by $V_i(b_{A,B}; \lambda_{-i})$ the value of firm i when we fix the level of investment of firm $-i$. Then,

$$\begin{aligned} V_i(b_{A,B}; \lambda_{-i}) = & \max_{\lambda_i} \Big\{ \lambda_i \left(v_1 + v_2 - c + V(p_2) \right) dt + \lambda_{-i} V(p_2) dt \\ & \qquad + (1 - \lambda_i dt - \lambda_{-i} dt - r dt) \, V_i(b_{A,B}; \lambda_{-i}) - \alpha C(\lambda_i) \cdot dt \Big\} \\ = & \max_{\lambda_i} \frac{\lambda_i (v_1 + v_2 - c_p + V(p_2)) + \lambda_{-i} V(p_2) - \alpha C(\lambda_i)}{r + \lambda_i + \lambda_{-i}} \end{aligned}$$

Unlike in state p_2, firm $-i$'s choice of investment affects firm i's incentives. Consider the first order condition for λ_i:

$$(r + \lambda_i + \lambda_{-i}) \alpha C'(\lambda_i) - \alpha C(\lambda_i) = (r + \lambda_{-i})(v_1 + v_2 - c_p) + r V(p_2)$$

Under Assumption 1, when firm $-i$ increases its investment λ_{-i}, the best response investment of firm i also increases. This means that investment by competing firms in this setting features strategic complementarities: as one increases investment the other will also increase their investment in research. This argument extends to other states, and other implementation/focus decisions, with the caveat that in the two asymmetric states b_A and b_B, the solution is necessarily asymmetric ($\lambda_A \neq \lambda_B$).

The only difficulty is in state b_n. In this state, it is possible that firms are so impatient that even under Assumption 1 firms' investments are strategic substitutes. In this case there are multiple investment equilibria, only in this state. As long as firms' discount rate r is not too large, this cannot happen.

The next step in characterizing the equilibrium is to determine implementation and focus decisions of the firms. The above discussion pins-down firms' equilibrium behaviour conditional on firms' implementation and focus choices. This also pins down firms' continuation values conditional on this behaviour, which we use to determine those choices. For instance, consider the decision of firm A when it is trailing in breakthroughs for the radical innovation ($\omega = b_B$). Its value can be determined by solving

$$\max_{e,p}(1-e)\Big[v_I - c_p + V_A(b_B)\Big] + e \cdot \Big[p \cdot \big(v_1 - c_p + V(p_1)\big) + (1-p) \cdot V(b_{A,B})\Big]$$

The $1-e$ term reflects the continuation value from achieving a breakthrough on the incremental innovation, whereas the e term reflects the continuation value from achieving a breakthrough on the radical innovation. Within this latter term, the firm must decide whether to patent (p term) or to maintain secrecy ($(1-p)$ term).[7]

An implication is that firms' focus will be bang-bang: they will either entirely focus on the radical innovation, or not at all. In order to maintain uniqueness, in the case of ties (a measure-zero set of parameter values) we assume that firms choose to delay implementation and to focus entirely on the radical innovation. These state-wise comparisons can be performed in each state, and determine each firm's optimal behaviour. This pins-down on-path coverage and implementation behaviour.[8]

3.1 Equilibrium Focus and Implementation Choices

The above section shows that there is a unique equilibrium, and discusses how it is found. However, it does little to give intuition for how firms actually behave, and how this behaviour depends on parameters. In the following sections, we exactly study these questions.

The first important point to discuss is firms' implementation and focus decisions.

[7] Although this latter comparison appears to assume that firm B doesn't publish in retaliation if firm A delays, firm B's incentives are the same, and so this is a sufficient condition to check.

[8] Notably, in state ω, the firm's decision of what innovation to pursue, and whether to implement after its next breakthrough is independent of the other firm's behaviour in state ω.

There are five possibilities for focus and implementation behaviour, determined by parameter values.

Definition 1. Given a Markov Perfect equilibrium, we say that firms are in region

- "Never Radical" (NR) if neither firm researches the radical innovation;
- "Give Up" (GU) if both firms research the radical innovation initially, but the firm who falls behind switches to the incremental innovation;
- "Delayed Implementation" (DI) if both firms research the radical innovation, and never implement the first breakthrough alone despite competition;
- "Catching-up Implementation" (CI) if both firms research the radical innovation, and the first breakthrough is implemented alone only by the firm that is catching up; and are in region
- "Immediate Implementation" (II) if both firms research the radical innovation, and immediately implement the first breakthrough when they achieve it.

The behaviour outlined in Definition 1 encompass all possibilities for firm behaviour, as the next result shows. In particular, as parameters change firm behaviour changes predictably.

Proposition 1. *In the unique stable symmetric equilibrium, firm behaviour follows one of the possibilities in Definition 1. As v_1 increases from 0, the equilibrium behaviour moves from $NR \to GU \to DI \to CI \to II$, possibly skipping some regions.*

To illustrate how the equilibrium structure depends on the value of each breakthrough in the radical innovation path, consider the example of quadratic research costs plotted in Fig. 1.[9] The figure shows the unique focus and publication decisions for each pair (v_1, v_2), given other parameters. As is intuitive, firms work on the deep story when one of two conditions are satisfied. Either $v_1 > v_I$, where it is beneficial to compete for at least the first stage of the radical innovation, or $v_1 + v_2$ is sufficiently

[9]Even in this setting, the equilibrium regions cannot be explicitly characterized. While it is possible to solve for equilibrium investment in many states $\omega = p_2, p_1, b_{A,B}$, the asymmetric states $\omega = b_A, b_B$ lead to coupled equations.

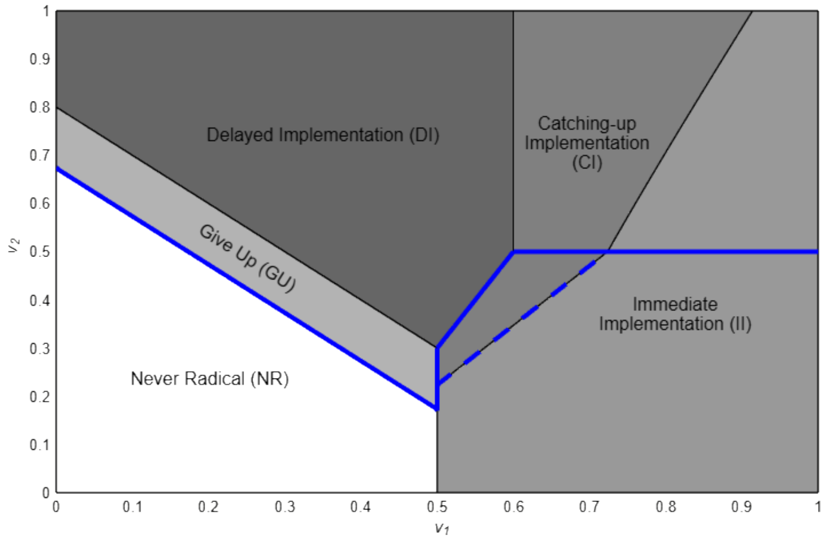


Figure 1: The competitive equilibrium for quadratic research costs $C(\lambda) = \frac{1}{2}\lambda^2$. Here $v_I = 0.5, c_p = 0.4, r = 0.1$, and $\alpha = 1$. The thick blue line marks the area below which the radical innovation may not be developed fully. Above the dashed blue line this only happens stochastically.

large, making the complete radical innovation sufficiently attractive to pursue despite competition and delayed gains. In addition, as suggested by the need for Definition 1, strategies vary conditional on working on the radical innovation. In particular, as the value of v_1 increases, firms are more likely to stay in the race, and are then more likely to partially implement the radical innovation. The following proposition, which is not specific to the example parameterization, summarizes this behaviour.

An important observation is that firms may choose to abandon the radical innovation partway through the race. Above the thick blue line in Fig. 1 both parts of the radical innovation are researched and eventually implemented. Below this threshold, either (i) firms do not work on the radical innovation at all (v_1 small), or (ii) early patenting (v_1 large) leads to incomplete development of the radical innovation: once the first breakthrough is implemented, firms switch to incremental innovations. This second possibility occurs when the market value of the second breakthrough v_2 is lower than the value of incremental breakthroughs v_I. As a result, in states where a change in region leads to implementation, for example if $\omega = b_{A,B}$ and we switch from DI to CI, further research in the radical innovation is halted.

3.2 The Shape of Innovation Races

The discussion above covers only firms' focus and implementation choices. These affect the extensive shape of the race, as they indicate where competition occurs, but do not necessarily correlate to the intensive margin of *how much* competition (i.e., investment) occurs in these states. It is straightforward that investment increases with profits while keeping focus and implementation choices fixed. This section discusses how the extensive shape of the race affects the intensive investment choices of firms. To study these effects, we compare how equilibrium investment changes in different states *at the borders* between regions.

Proposition 2. *Firm investment λ discontinuously changes along the border of two regions. Let $\lambda^h(\omega)$ in what follows denote equilibrium investment on the radical innovation in state ω and region h.*

(i) ***Initial Investment.***

Investment decreases in the future threat of appropriation:

$\lambda^{GU}(b_n) > \lambda^{DI}(b_n), \lambda^{CI}(b_n)$ *along their border, and* $\lambda^{DI}(b_n) > \lambda^{CI}(b_n)$ *along their border. Moreover, there exists a* $\overline{v}$ *such that* $\lambda^{CI}(b_n) > \lambda^{II}(b_n)$ *if and only if* $v_2 > \overline{v}$ *along their border.*

(ii) ***Second-stage Investment.***

Investment increases with competition and the threat of appropriation:

$\lambda_k^{GU}(b_i) < \lambda_k^{DI}(b_i), \lambda_k^{CI}(b_i)$ *along their border, and* $\lambda_k^{DI}(b_i) < \lambda_k^{CI}(b_i)$ *along their border, for both* $k = i, j$.

Early implementation discourages investment:

$\lambda^{DI}(b_{A,B}) > \lambda^{CI}(p_1) = \lambda^{II}(p_1)$ *along their border. Moreover, there exists a* $\overline{v}'$ *such that* $\lambda_i^{CI}(b_i) > \lambda^{II}(p_1)$ *if and only if* $v_2 < \overline{v}'$ *along their border.*

As this result shows, focus and patenting choices shape equilibrium investment across development stages. In general, more competitive research paths, in which rival firms remain active and have incentives to patent early, lead to lower investment in early stages of development. However, the effect on later stages of development is not monotonic. In states where a breakthrough has been achieved, greater competition increases effort when it does not automatically lead to implementation. When greater competition leads to immediate implementation, the incentive to continue development is lower and investment tends to decrease. While this can be compensated by an extra firm working on second-stage development, a standard information externality, research can be halted as a result of patenting for low enough v_2.

3.3 Firms' Values

Interestingly, although the relationship between firms' investment across regions depends on the state of the race, the same is not true for firms' values. In order to understand how policy changes will be received by firms and dictate entry, we must understand how their values change with the shape of the race. We show next how firms' values compare at the borders across regions.

Proposition 3. *At the borders between regions, we have the following relationship between firms' values.*

(i) Firms prefer to be in the region where their opponent gives up, in all initial and second-stage states: $V_{i,GU}(\omega) > V_{i,DI}(\omega)$ *for* $\omega = b_n, b_i$*, and* $V_{j,GU}(b_i) = V_{j,DI}(b_i) = V_j(p_2)$ *for* $\omega = b_i$*.*

(ii) Firms prefer the region in which implementation is delayed: $V_{i,DI}(\omega) > V_{i,CI}(\omega)$ *for* $\omega = b_n, b_i, b_j$*.*

Proposition 3 shows that, unlike firms' investment which varies drastically across states, firms' preference over regions is consistent throughout the race: they dislike competition, and conditional on competition they prefer their opponents to commit to a long race. Early implementation hurts the leading firm and its opponent. Intuitively, the latter's inability to commit to delay implementation pushes the leading firm to invest more, decreasing its chance to make any profits.

4 Innovation Policy: Lower Fees or Subsidize?

From the previous section it is clear that firms incentive to patent and competition throughout the research race are key determinants of investment decisions. We study in this section how these are shaped by two instruments actively used in innovation policy: R&D subsidies and patent fees.

An important feature of our model is that it allows us to study different mechanisms by which policy changes affect firm innovation. There are two main margins along which innovation investment decisions may change. The first is the straightforward margin of the magnitude of research investment. This is captured in our model through firms' choices of their λ_i's. The second margin is subtler: which projects do they decide to pursue, and how far do they push these projects. This is captured in our model through firms' choice of patenting and focus decisions. This is an important question for policy analysis. Policies that encourage firms to invest more, but to focus on incremental innovations that have little social benefit may be considered successful if policymakers look only at magnitude increases. Hence, in analyzing the impact of policies it is important to look at both margins.

Definition 2. A parameter change is said to

(i) *increase investment within regions* if, for all values of (v_1, v_2) such that equilibrium patenting and focus decisions don't change after the parameter change, equilibrium investment increases in each state.

(ii) *increase focus on the radical innovation* if the region *NR* shrinks.

(iii) *encourage continuation* if region *II* shrinks and region *DI* expands.

It is said to *place emphasis on the radical innovation* if it both increases focus on the radical innovation and encourages continuation.

Subsidizing Research Costs. A common policy instrument to promote innovation is the direct subsidization of research costs, typically implemented through R&D tax credits or deductions. In our model, this corresponds to a reduction in α, the scale factor for the marginal cost of research investment. For example, a 10% reduction in α reduces research costs by 10% for any investment level λ.

Importantly, R&D subsidies affect firms' innovation decisions through multiple channels. The dominant focus in both the policy debate and the existing literature is the intensive-margin effect: by lowering research costs, subsidies increase firms' incentives to invest more in innovation overall.[10] This intensive margin of innovation

[10]Seminal papers on the effectiveness of these policies include Bloom, Griffith, and Van Reenen (2002) and Atkeson and Burstein (2019).

is captured in our model through firms' choice of λ_i. The strategic complementarity of firms' research investments amplifies this effect: firms will increase their investments by more when they face competition. Hence, a decrease in α has a larger impact on the race for the radical innovation than it does on incremental innovations.

Changes in research costs also affect the margin between the radical and incremental innovations. At the margin, lower research costs favour projects with several stages of development both since they are more costly and more competitive. Likewise, when research costs are lower, firms rely more on heavy investment rather than early patenting to preserve the value of their breakthroughs. Intuitively, investment serves as a substitute for early patenting to protecting proprietary knowledge. These results are summarized in the following proposition.

Proposition 4. *Fix v_I, c_p, and r. A decrease in research costs from α to α'*

(i) increases investment within regions; and

(ii) places emphasis on the radical innovation.

Thus, R&D subsidies not only achieve stronger investment overall, but also tilt firms toward deeper innovations and late patenting. As we saw earlier the latter generally favours investment in earlier stages of development and prevents patenting from discouraging it later on.

Changing Patenting Costs. A key drawback of R&D subsidies is their fiscal cost. An alternative way to influence innovation incentives is by altering the costs of implementing new technologies. In this context, the role of patenting costs in shaping firms' innovation choices remains relatively underexplored.[11]

On the surface, since patenting costs decrease firms' benefit from innovating and patenting research, they should be avoided. Strategic complementarities magnify this effect: one firm decreasing their effort leads the other to decrease effort by more than they would in the absence of competition. Hence, at the intensive margin patenting costs depress innovation.

However, the effect of patenting costs is also felt differently by firms pursuing incremental versus radical innovations. Since these costs are fixed and independent

[11] See Hall and Harhoff (2012) for a review.

of the value and type of the patent, by raising patent fees policymakers encourage higher value deep innovations, both because their payoffs are larger and because patent fees are more heavily discounted due to competition and bundling. Hence, at the extensive margin, patenting costs increase firms' focus on radical innovations.

Moreover, an increase in patenting costs lowers the incentive to protect preliminary breakthroughs through patenting. As we saw earlier this encourages investment in earlier stages of development and prevents early patenting from discouraging later investment. These results are summarized in the following proposition.

Proposition 5. *Fix v_I, α, and r. An increase in implementation costs from c_p to c_p'*

(i) decreases investment within regions; but

(ii) places emphasis on the radical innovation.

This result highlights the potential of patent fees as a policy instrument. In settings where fiscal capacity is limited or additional taxation is highly distortionary, adjusting patent fees can encourage firms to pursue radical innovations, increase early-stage investment, and sustain research efforts through later stages of development.

4.1 Optimal Policy

The above section considers the general effects of changes in important parameters c_p and α. In this section we consider a more applied exercise of discussing the optimal values for these parameters given a specific policy objective.

Innovation policymakers aim to spur innovation. In our setting with multiple types of innovations, the policymaker may care differentially about the innovation that they encourage. A natural setting is that in which incremental innovations are of little social value relative to radical innovations. In this setting, the policymaker simply may wish to minimize the time until the radical innovation is finished. Focus on the radical innovation requires high c_p or low α. However, conditional on firms working on the radical innovation their individual investment and publication decisions determine the optimal policy. This results in nontrivial optimal policy.

Let $T(c_p, \alpha; v_1, v_2)$ denote the expected time until the radical innovation is completely developed and patented. Here, the policy maker aims to minimize $T(c_p, \alpha; v_1, v_2)$ with respect to policy parameters (c_p, α). Proposition 6 characterizes some dynamics of the optimal policy.

Proposition 6. *We have the following:*

(i) The value of α *that minimizes expected time is zero:* $\operatorname{argmin}_{\alpha \geq 0} T(c_p, \alpha; v_1, v_2) = 0$.

(ii) The value of implementation costs c_p *that minimizes expected time is not always zero: there exist* (v_1, v_2) *such that* $\operatorname{argmin}_{c_p \geq 0} T(c_p, \alpha; v_1, v_2) > 0$*. Moreover,*

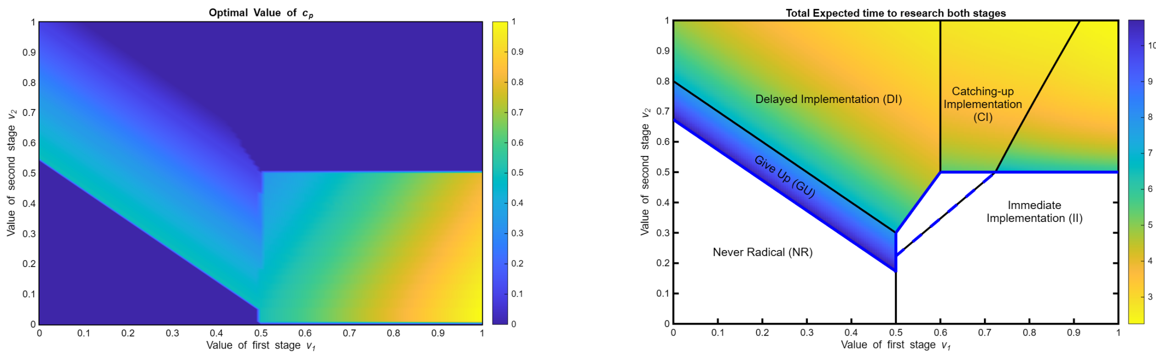
- *For* v_2 *sufficiently low,* $\operatorname{argmin}_{c_p \geq 0} T(c_p, \alpha; v_1, v_2)$ *is decreasing in* v_1 *for low* v_1 *and increasing in* v_1 *for large* v_1*.*
- *For* v_2 *sufficiently high,* $\operatorname{argmin}_{c_p \geq 0} T(c_p, \alpha; v_1, v_2) \equiv 0$ *for all* $v_1 > 0$*.*

Unsurprisingly, the value of α that minimizes the expected time to finishing the race is zero: by removing research costs entirely, firms are incentivized to invest an unbounded amount in research. Moreover, since decreasing research costs α places emphasis on the radical innovation, this increase in the intensive margin does not negatively impact firms' incentives to research the radical innovation.

The story is quite different for implementation costs. As we have seen, implementation costs impose a trade-off between the extensive and intensive margins of innovation. Within a given region of equilibrium behaviour, the lower the value of implementation costs, the higher equilibrium investment. At the same time, increasing implementation costs can encourage firms to focus on the radical innovation and delay patenting. These together increase the range of radical innovations that are pursued in equilibrium and increase investment in initial stages.

Considering the quadratic cost case, Figure 2a plots the value of c_p that minimizes T for different pairs (v_1, v_2) given a value of α. We see that the optimal implementation cost is not generally equal to zero. Intuitively, as long as firms work on the radical innovation until the last stage, the policymaker wants to decrease c_p as much as possible so that firms increase investment and benefit from the information externalities of early publication. However, for low enough values of v_2 the policymaker wants to keep c_p positive for two possible reasons. First, if $v_1 > v_I$, the optimal policy is to make c_p just as low as to make the firms indifferent between publishing early or not whenever $v_2 < v_s$, since lowering c_p further would lead to halting research before the second stage is reached. Second, if $v_1 < v_I$, the optimal policy is to lower c_p until firms are indifferent between switching towards incremental innovation.

This shows the costs associated with uniform patent fees. While a policymaker would like implementation costs to be zero for highly valued radical innovations, encouraging investment and information disclosure, this is costly for radical innovations with low private value in late stages of development, where low fees lead firms to patent early and focus on incremental innovations.[12]



(a) Value of implementation costs that minimizes expected time to completion of the radical innovation. Here, $C(\lambda) = \frac{1}{2}\lambda^2$, $\alpha = 1$, $v_I = 0.5$, $r = 0.1$.

(b) For a given $c_p = 0.4$, the total expected time to completion of the radical innovation $T(c_p, \alpha; v_1, v_2)$.

Figure 2: Optimal Patent Fees

Finally, note that R&D subsidies and patent fees are substitutes in fostering emphasis on the radical innovation. Higher R&D subsidies mapping to a lower α, incentivize firms to delay patenting and focus on the radical innovation, so that the necessary patent fee to maintain focus on the radical innovation is lower for any pair (v_1, v_2).

5 The Innovation Loop: How Technology Shapes Research

As a model of innovation direction and investment, our framework highlights a channel through which innovation feeds back into future research. The standard narrative emphasizes how new products or technologies enable follow-on innovations by serving as inputs into subsequent development.[13] In contrast, this section focuses on how technological advances reshape the research process itself, affecting how firms

[12]Implementation costs strictly above a positive lower bound $\underline{c} \in \mathbb{R}_{++}$ may arise even for large v_2 when the policy space is constrained (e.g., if subsidies are not feasible). This reflects the non-monotonic effects of implementation costs on firms' publication and research decisions.

[13]See, for example, Bresnahan and Trajtenberg (1995) and Galasso and Schankerman (2015).

experiment, invest, and release innovations.

The pharmaceutical industry provides a useful example. Over the past decades, a series of technological breakthroughs have dramatically reduced the cost of early-stage research and experimentation. Advances in genomics and sequencing sharply lowered the cost of identifying disease mechanisms and biological targets. More recently, gene-editing technologies such as CRISPR-cas9 have transformed experimental biology by making precise genetic modification faster, cheaper, and more scalable.[14]

Arguably, implementation costs have not declined proportionally. Clinical trials remain lengthy and expensive, and regulatory approval procedures are highly structured, involving substantial compliance costs. The model therefore predicts that such technological change encourages deeper, multi-stage innovation and greater continuation of research before commercialization.

In contrast, the news media industry provides a particularly transparent setting in which technological change has dramatically reduced dissemination costs. In what follows, we discuss how our model can help explain observed changes in both frequency and quality of information based on recent technological change. An extension of the model provides insights on how dissemination costs determine the entry of copiers and, hence, affect information production through a novel channel.

5.1 Research in the News Industry: Quality and Frequency

Over the past decades, technological progress has profoundly altered the organization of news production. News provision has shifted from discrete 24-hour reporting cycles to the continuous production and updating of information throughout the day. While the transition from print to online platforms and social media has substantially reduced distribution costs, recent advances in digital technologies and generative AI have also lowered the cost of producing content.

Although these technological changes appear to reduce both production and distribution costs for news providers, they have also raised concerns about information quality and the spread of misinformation. The European Commission has highlighted these concerns, noting that intensified competition to publish quickly, rather than over a full 24-hour reporting cycle, may reduce fact checking and increase errors (Martens

[14] On the decline in sequencing costs, see National Human Genome Research Institute (2023). On the transformative role of CRISPR-Cas9 for experimental studies, see Doudna and Charpentier (2014).

et al. (2018)).[15] In parallel, survey evidence suggests that public trust in the media has declined steadily (Pew Research Center (2020) and Gallup, Inc. (2023)), with respondents citing concerns about accuracy and deliberate attempts to mislead.

Existing work has largely focused on misinformation and bias in news reporting. In contrast, we use our innovation framework to show how standard competitive forces in research races, interacting with recent technological developments, can account for apparent changes in both the frequency and quality of news output.

We reinterpret the model as a race between two firms to publish news stories. Each breakthrough corresponds to the acquisition of new information that contributes to building a story suitable for publication. First publishers of content obtain a payoff v and others do not benefit from reposting this information.[16]

Innovations that require multiple breakthroughs represent high-value news stories that unfold over several stages of development. Importantly, the second stage can be interpreted as the acquisition of additional information that improves the accuracy, of the story: fact-checking. By contrast, simple innovations correspond to news content with limited competition and a largely repeatable structure, such as routine updates or standardized reporting. Examples include weather reports, basic financial summaries, or repackaged press releases, a category often described as "churnalism."

As discussed above, recent technological changes have drastically decreased the cost of disseminating content once it has been produced. In our model, this change corresponds to a reduction in c_p. Proposition 5 shows that lower publication costs tilt firms toward simple, repeatable stories, such as what is commonly referred to as "churnalism", and toward partial publication of deeper stories. The intuition is straightforward. Cheap publishing favours easy-to-produce content and creates incentives to release information as soon as it becomes available, in order to preempt competitors.[17] As a result, firms devote more effort to simple stories and are more likely to leave complex stories "incomplete" or "unverified", since early publication reduces incentives for further development and disclosure.

These mechanisms are consistent with a decline in the perceived quality of pub-

[15] See also Allcott and Gentzkow (2017) and Allcott, Gentzkow, and Yu (2019) for evidence on the penetration and impact of misinformation.

[16] This assumption captures coarsely the well-documented originality premium in news media (Franceschelli (2011) and Cagé, Hervé, and Viaud (2020)).

[17] This often leads to reporting errors or a decrease in accuracy.

lished content. Publication frequency, however, may respond in either way to declines in publication costs. Lower publication costs mechanically increase the number of releases if investment strategies remain unchanged. Yet, when lower costs also alter disclosure decisions, the effect on publication frequency becomes ambiguous: earlier publication increases the number of releases, while weaker incentives to complete later stages reduce investment depth.

While other, less visible technological improvements that reduce production costs could increase publication rates by encouraging greater investment, they cannot account for a decline in news quality through the lens of our model. A decrease in α favours deeper stories and later publication, reducing the likelihood that firms leave stories incomplete. By contrast, our theory shows that a substantial decline in publication costs provides a clear and coherent explanation for consumers' perceptions of recent developments in the news market.

In the next section, we examine how increased entry of copiers in the industry is associated with these technological changes, and how this entry shapes firms' publication and coverage choices.

5.1.1 Publication Costs and The Entry Of Copiers

As in many other industries, the expansion of internet access has been accompanied by an appropriability problem, namely the entry of agents who copy and redistribute content produced by others for their own profit.[18] Using French data, Cagé, Hervé, and Viaud (2020) document a substantial originality premium in news markets and show that online copying is pervasive, with most news articles replicated within minutes of publication. In this section, we argue that these patterns are a direct consequence of technological progress that has sharply reduced sharing costs, and we study how this affects news production incentives.

We extend the model by introducing a copier that reposts information published by news providers. The copier does not engage in information production and simply appropriates part of the value generated by original reporting. Specifically, we assume that upon publication immediate copying captures a fraction $\beta \in [0, c_p/v_I) \subset [0, 1)$

[18]This concern has motivated a large literature on internet piracy in the music and television industries, see for example Waldfogel (2012).

of the payoff v that a firm would obtain in isolation. Crucially, the copier incurs a publication cost $c_{p,C} = c_p$ and therefore operates only when $\beta v > c_p$.

The presence of copiers amplifies the effect of decreasing sharing costs. When these decrease, copiers are attracted to a wider range of stories, decreasing their attractiveness to active firms. Crucially, since copiers are attracted to high-payoff stories, reductions in publication costs disproportionately affect incentives to pursue deep reporting.

The effect of decreasing c_p on active firm incentives has been studied in Proposition 5. We isolate how changing sharing costs affects firm incentives through the entry of copiers by fixing c_p for active firms, and changing $c_{p,C}$. Consider the effect of copying on stories with $v_1, v_2 \in [0, \overline{v}]$, for some $\overline{v} \in \mathbb{R}$.

When publication costs are large enough, there is no copying in equilibrium because $\beta \cdot (v_1 + v_2) < c_{p,C}$ for all v_1, v_2. If publication costs decrease sufficiently, high-value stories are the first to be targeted by copiers. This creates a discontinuity in firm behaviour at the line $\beta \cdot (v_1 + v_2) = c_{p,C}$.

Intuitively, sufficiently high-value stories will be treated as if they were of lower value. The effect is more nuanced than this, however. Since copying only occurs if the publication is of sufficiently high-value, active firms are encouraged to break stories apart through early publication in order to avoid the effects of copying.

As $c_{p,C}$ decreases further, less valued multi-stage stories will be copied. This can encourage firms to switch to simple stories in a non-monotonic fashion: multi-stage stories just valuable enough to be copied may be ignored by firms because of this appropriation.

Additionally, when sharing costs become so low that even partial stories are copied, the previous incentive to unbundle stories disappears and continuation after early publication becomes less desirable, requiring $(1 - \beta)v_2 > v_I$.

Overall this suggests that reductions in sharing costs, by attracting copiers that erode appropriability for high-value stories, lead to earlier publication, a shift toward simple stories, and a higher incidence of incomplete reporting. This entry channel reinforces our broader intuition about how sharing costs shape research incentives in the news industry. Proposition 7 formalizes the effects of copier entry on firms incentives.

Proposition 7 (Copier entry). *Fix v_I, α, β, r and the publication cost of traditional firms c_p. A decrease in the copier's publication cost from $c_{p,C}$ to $c'_{p,C}$ results in:*

(i) lower focus on the multi-stage story;

(ii) early publication becomes more attractive relative to delayed publication if only the bundled deep story becomes copied:

$$c_{p,C} > \beta(v_1 + v_2) > c'_{p,C} > \beta \max\{v_1, v_2\}; \text{ and}$$

(iii) delayed publication becomes more attractive relative to early publication if the bundled story is already copied and intermediate publications become copied,

$$\beta(v_1 + v_2) > c_{p,C} > \beta \max\{v_1, v_2\} > c'_{p,C}.$$

If, additionally, extra copying affects the second stage, $c_{p,C} > \beta v_2 > c'_{p,C}$, firms are more likely to halt research after intermediate publication.

6 Conclusion

A central policy debate in Europe concerns the slowdown in productivity growth and how to redesign institutions to foster innovation. Much of this discussion has focused on deregulation and the design of R&D subsidies. At the same time, mounting demographic pressures are tightening fiscal constraints, limiting the scope for policies that rely on large public expenditures.

Our paper proposes the design of patent fees as an effective policy tool to incentivize high-value disruptive innovation. By increasing the cost of implementing new innovations, higher patent fees encourage firms to focus on multi-stage innovations. Additionally, this prevents them from implementing intermediate breakthroughs, which can discourage follow-on innovation. This is specially relevant when high R&D costs push firms to protect their intellectual property with excessive patenting of preliminary breakthroughs.

Our paper provides insights on how technological progress can affect follow-on innovation not just through knowledge creation, but on whether firms choose to work in secrecy and on their research direction. We use this framework to provide a novel supply-side explanation for the increasing mistrust in media. Reductions in sharing costs brought by the digital era increase the incentive for firms to focus on "basic" stories and to publish information as soon as possible to preempt competitors, with less fact-checking and possibly incomplete reporting. Additionally, this attracts copiers that expropriate profits, further discouraging firms from working on high-value stories.

Overall, our paper highlights how both policy and technological change can shape the innovation path by altering the costs and benefits of innovating and implementing new technologies. We show that decreasing implementation costs can be detrimental when we factor in strategic competition between innovators.

Finally, the paper delivers a set of testable empirical implications that we leave for future research. Across countries, higher patenting fees, stricter filing requirements, or more generous R&D subsidies should be associated with a higher share of multi-stage technologies and longer development cycles. Over time, technological changes that reduce implementation costs, such as digital marketing or automated legal tools, should lead to a rise in incremental innovations and early-stage patenting. In contrast, advances that lower research costs, such as AI-assisted programming or improved mathematical algorithms, should shift firms toward deeper innovation strategies.

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A Proofs

In this section we prove the main results in the text.

A.1 Proof for Section 3

In this section, abuse notation and write $C(\lambda) = \alpha C(\lambda)$. This is just meant to simplify notation.

A.2 Preliminaries

Given a state ω, let W_i^i denote the firms' continuation value from achieving a breakthrough. Similarly, let W_i^{-i} denote the firm's breakthrough from his opponent achieving a breakthrough. Notice that both of these continuation values come from fixing both firms' continuation behaviour. Finally, fix the opposing firms' value of investment, λ_{-i}.

Then, similar to the derivation as derived in the main text,

$$V_i(\omega) = \max_{\lambda_i} \frac{\lambda_i W_i^i + \lambda_{-i} W_i^{-i} - C(\lambda_i)}{r + \lambda_i + \lambda_{-i}}$$

The first-order condition in terms of λ_i is equal to

$$W_i^i - V_i(\omega) = C'(\lambda_i)$$

Since this relies on the implicit value of $V_i(\omega)$, this is not a solution. Simple algebra means that the first-order condition is equivalent to

$$(r + \lambda_i + \lambda_{-i})C'(\lambda_i) - C(\lambda_i) = rW_i^i + \lambda_{-i}\left(W_i^i - W_i^{-i}\right)$$

The right-hand side is independent of λ_i and the left-hand side is strictly increasing in λ_i (due to the strict convexity of C). This implies that for each λ_{-i} there exactly one λ_i which solves this equation. By the quasi-concavity of the objective function $V_i(\omega)$, this will be the maximizer.

Now consider the effect of increasing λ_{-i}. The contribution from the left-hand side is $C'(\lambda_i)$, while the contribution from the right-hand side is $W_i^i - W_i^{-i}$. This implies that an increase in λ_{-i} will imply an increase in λ_i if and only if W_i^{-i} is larger than $V_i(\omega)$.

For there to be an equilibrium, the pair $(\lambda_i, \lambda_{-i})$ must also satisfy

$$(r + \lambda_{-i} + \lambda_i)C'(\lambda_{-i}) - C(\lambda_{-i}) = rW_{-i}^{-i} + \lambda_i \left(W_{-i}^{-i} - W_{-i}^{i}\right)$$

Let $\varphi(\lambda_{-i})$ denote the solution to the first equation, as a function of λ_{-i}, and $\psi(\lambda_i)$ denote the solution to the first equation, as a function of λ_i. By the implicit function theorem, we have that

$$\varphi'(\lambda_{-i}) = -\frac{C'(\varphi(\lambda_{-i})) - (W_i^i - W_i^{-i})}{(r + \varphi(\lambda_{-i}) + \lambda_{-i})\, C''(\varphi(\lambda_{-i}))}$$

Some straightforward algebra shows that (writing $\lambda_i = \varphi(\lambda_{-i})$ for succinctness)

$$\begin{aligned}\varphi''(\lambda_{-i}) = &- \frac{(r + \lambda_i + \lambda_{-i})C''(\lambda_i)^2 \cdot \varphi'(\lambda_i)}{(r + \lambda_i + \lambda_{-i})^2 C''(\lambda_i)^2} \\ &+ \frac{\left[(r + \lambda_i + \lambda_{-i})C'''(\lambda_i)\varphi'(\lambda_i) + (\varphi'(\lambda_i) + 1)C''(\lambda_i)\right](C'(\lambda_i) - W_i^i + W_i^{-i})}{(r + \lambda_i + \lambda_{-i})^2 C''(\lambda_i)^2}\end{aligned}$$

If $C'(\lambda_i) - W_i^i + W_i^{-i}$ is negative so that φ' is positive, the above is sign equivalent to

$$-2(r + \lambda_i + \lambda_{-i})C''(\lambda_i)^2 + \left[(r + \lambda_i + \lambda_{-i})C'''(\lambda_i) + C''(\lambda_i)\right] \cdot \left[C'(\lambda_i) - W_i^i + W_i^{-i}\right]$$

which is negative by the convexity of C. Hence, whenever $\varphi'(\lambda_{-i}) > 0$, φ is concave.

Additionally, notice that φ cannot go from increasing to decreasing. To see this, observe that the numerator of $\varphi'(\lambda_{-i})$ is increasing in φ. So, φ' cannot become negative, else ϕ would immediately be pushed back to $C'(\varphi) = W_i^i - W_i^{-i}$. These together imply that either φ is increasing for all λ_{-i}, or is decreasing for all λ_{-i}. Similar conclusions apply to ψ.

By these observations, either ψ and φ are both increasing in a neighbourhood of the equilibrium or they are both decreasing. Recalling that at an equilibrium we have

$$C'(\lambda_i) = W_i^i - V_i(\omega)$$

we hence see that either at all equilibrium

$$V_i(\omega) \geq W_i^{-i}$$

or

$$V_i(\omega) < W_i^{-i}$$

Case 1: $V_i(\omega) \geq W_i^{-i}$ and $V_{-i}(\omega) \geq W_{-i}^i$. By the concavity of φ, ψ, there are at most two solutions to the equation $\lambda_i - \varphi(\psi(\lambda_i)) = 0$. These correspond exactly to the equilibria. Moreover, one of these equations must not be stable: at the lower solution a small increase in λ_{-i} leads to a larger increase in λ_i, causing instability.

Case 2: $V_i(\omega) \geq W_i^{-i}$ and $V_{-i}(\omega) < W_{-i}^i$. In this case, φ is increasing but ψ is decreasing. In this case there is at most one solution to $\lambda_i - \varphi(\psi(\lambda_i))$ as it is an increasing function. The corresponding other case is handled similarly.

Case 3: $V_i(\omega) < W_i^{-i}$ and $V_{-i}(\omega) < W_{-i}^i$. In this case, both φ and ψ are decreasing functions. The idea in this case is that each firm would like the other to do the work of achieving the first breakthrough.

This implies that there is at most one symmetric solution to the two equations.

Proof of Theorem 1.

Lemma A.1. In state $\omega = p_2$, there is one sub-game perfect equilibrium. It is symmetric.

Proof. In this state, it is clear that $W_i^i = v_I - c + V_i(p_2)$ and $W_i^{-i} = V_i(p_2)$. Hence, the optimal choice of investment λ_i does not depend on λ_{-i}. □

Lemma A.2. In state $\omega = p_1$, there is one stable sub-game perfect equilibrium. It is symmetric.

Proof. If $v_2 < v_I$, then both firms abandon the deep innovation and we will hence have the equilibrium the same as in state $\omega = p_2$.

Otherwise, we have $W_i^i = v_2 - c + V_i(p_2)$ and $W_i^{-i} = V_i(p_2)$. Since it is necessarily the case that $V_i(\omega) \geq V_i(p_2)$ for all ω, this means that we are in the case where both φ and ψ are increasing.

This means that there are possibly two steady-states of the function $f(\lambda_i) = \varphi(\psi(\lambda_i))$. As observed above, only the larger of these will be stable. Since $\psi = \varphi$ here, we conclude that it is symmetric. □

Lemma A.3. Assume that firms do not implement early in state $\omega = b_{A,B}$. In state $\omega = b_{A,B}$, there is one stable sub-game perfect equilibrium. It is symmetric.

Proof. By the above, it is sufficient to check behaviour within this state. We have that $W_i^i = v_1 + v_2 - c + V_i(p_2)$ and $W_i^{-i} = V_i(p_2)$. As in the case above, we have that both φ and ψ are increasing. We conclude similarly to the above. □

Lemma A.4. In state $\omega = b_A$ there is one stable sub-game perfect equilibrium. There is similarly a unique stable sub-game perfect equilibrium in state $\omega = b_B$.

Proof. We focus on the proof in the case of $\omega = b_A$. The case for $\omega = b_B$ is similar. First consider implementation and coverage behaviour.

Now, consider firms' implementation and coverage behaviour. The firm who catches up will publish if

$$V_A(b_{A,B}) < v_1 - c + V(p_1)$$

As well, the lagging firm will only pursue the deep innovation if

$$v_I - c + V(b) \leq \max\left\{V_A(b_{A,B}), v_1 - c + V(p_1)\right\}$$

This last condition stems from the following. If firm B does not implement early, but $V_A(b_{A,B}) < v_1 - c + V(p_1)$, then firm A will respond by implementing early.

First, assume that the leading firm A does not implement early. Then, we have several cases:

Case 1. Firm B switches to the incremental innovation. In this case, strategic incentives have disappeared, and so the leading firm has a unique solution, as in state $\omega = p_2$. Similarly, firm B maximizes as it does in state $\omega = p_2$. For firm B to give up in state $\omega = b_A$, it must be the case that

$$v_1 - c + V(p_1) < v_I - c + V(p_2)$$

and

$$V(b_{A,B}) < v_I - c + V(p_2)$$

Notice that here the comparison is $V(p_2)$ and not $V_B(b_A)$ because, conditional on leaving the deep story firm B will not choose to re-enter the race. This cane be seen

Case 2. Firm B implements upon achieving a breakthrough. For firm A we have

$$W_A^A = v_1 + v_2 - c + V(p_2), \quad W_A^B = V(p_1)$$

and for firm B we have

$$W_B^B = v_1 - c + V(p_1), \quad W_A^B = V(p_2)$$

In both cases we have $V_i(\omega) \geq W_i^{-i}$. In A's case, it is because it has the ability to publish immediately. In firm B's case, it is because of the standard bound. For this to hold, it must be the case that

$$v_1 - c + V(p_1) > v_I - c + V(p_2), V(b_{A,B})$$

Case 3. Firm B chooses to delay the breakthrough For firm A we have

$$W_A^A = v_1 + v_2 - c + V(p_2), \quad W_A^B = V(b_{A,B})$$

and for firm B we have

$$W_B^B = V(b_{A,B}), \quad W_A^B = V(p_2)$$

To see why $V(b_{A,B}) < V_A(b_A)$, observe that just means that firm A is closer to losing the race for the deep innovation: there are no informational benefits. Again in this case we have that there is one stable solution, and strategic complementarities. □

Lemma A.5. In state $\omega = b_A$ there is one stable sub-game perfect equilibrium. There is similarly a unique stable sub-game perfect equilibrium in state $\omega = b_B$.

Proof. Consider first the possibilities for firms' behaviour upon achieving a breakthrough. Firm A's continuation value will be $V_A(b_A)$. This value will importantly depend on the behaviour of firm B following a breakthrough of firm A.

Firm A will implement after an initial breakthrough if and only if

$$V_A(b_A) < v_1 - c + V(p_1)$$

Similarly for firm B. There are hence two cases.

Case 1. The leading firm chooses not to implement early. Then, we have

$$W_i^i = V_i(b_i), \quad W_i^{-i} = V_i(b_{-i})$$

In this case, the lagging firm clearly does not benefit from their opponent being ahead in the race. Hence, in this case as well we have that there is one stable equilibrium.

Case 2. The leading firm chooses to implement early. Then, we have

$$W_i^i = v_1 - c + V(p_1), \quad W_i^{-i} = V(p_1)$$

In this case it is possible for φ and ψ to be decreasing. This occurs when $V(p_1)$ is sufficiently large relative to firms' values at the start of the race.

Subcase 1. φ is decreasing. In this case, by symmetry, ψ must also be decreasing. This means that the opposing firms' investment λ_{-i} is decreasing with respect to λ_i, and vice versa. This corresponds to the case when the value from reaching the first stage of the radical innovation is small, but the benefit from the second stage of the innovation is very large.

In this case, there may exist multiple equilibria. However, there will still only be one symmetric equilibrium. It will be the unique solution to

$$(r + 2\lambda)C'(\lambda) - C(\lambda) = rW_{-i}^{-i} + \lambda \left(W_{-i}^{-i} - W_{-i}^{i}\right)$$

In this case there may also exist other equilibria, but they are not symmetric. Moreover, this case cannot occur if r is sufficiently small. In that case, it will always be that

$$\max_{\lambda} \frac{\lambda(v_1 - c + V(p_1)) - C(\lambda)}{r + \lambda} \geq \max_{\lambda} V(p_1)$$

whenever $v_1 - c + V(p_1) > V(b_A)$.

Hence, as long as r is not too large, this case does not exist.

Subcase 2. φ is increasing. This subcase corresponds to the scenario when either free-riding incentives are not too large. In this case, as before, we have a unique stable equilibrium. It is symmetric. □

We can rewrite things. There still will be a symmetric equilibrium, even if r is sufficiently high. It is just that there may be other equilibria in the state b_n. Maybe reframe it in terms of: there exists a unique stable, symmetric equilibrium. If $r \leq \overline{r}$, then it is the unique stable equilibrium.

These results together complete the proof of Theorem 1. □

Proof of Proposition 1. Let $V_i(\omega)$ denote firms' values in the unique stable symmetric equilibrium. We drop the subscript i when ω is a symmetric state.

Before we show the regions change with respect to v_1, we restate the equations that determine each region. Once these equations are clearly stated, it is straightforward to show the result.

Never radical, NR. Here, it must be that it is not beneficial to research the radical innovation, regardless of my opponents' decision. So, it is the case that

$$\begin{aligned} v_I - c + V(p_2) &> \max_{\lambda} \frac{\lambda(v_1 + v_2 - c + V(p_2)) - C(\lambda)}{r + \lambda} \\ v_I - c + V(p_2) &> v_1 - c + V(p_1) \end{aligned}$$

Give up, GU. Here, it must be valuable to research the radical innovation initially, conditional on the opponent dropping-out.

$$\begin{aligned} v_I - c + V(p_2) &< \max_{\lambda} \frac{\lambda(v_1 + v_2 - c + V(p_2)) - C(\lambda)}{r + \lambda} \\ v_I - c + V(p_2) &> v_1 - c + V(p_1) \end{aligned}$$

Moreover, it must be optimal to not implement initially, and it must be optimal to not continue the race once the firm falls behind.

$$v_I - c + V(p_2) > V(b_{A,B})$$

Delayed Implementation, DI**.** The conditions are as follows:

$$\begin{aligned}
&v_I - c + V(p_2) < V_A(b_A)\\
&v_I - c + V(p_2) < V(b_{A,B})\\
&v_1 - c + V(p_1) < V(b_{A,B})
\end{aligned}$$

Note as well that the first inequality is implied by the second since $V_A(b_A) \geq V(b_{A,B})$.

Catching-up Implementation, CI**.** The conditions are as follows:

$$\begin{aligned}
&v_1 - c + V(p_1) > V(b_{A,B})\\
&v_I - c + V(p_2) < v_1 - c + V(p_1)\\
&V_A(b_A) > v_1 - c + V(p_1)
\end{aligned}$$

Immediate Implementation, II**.**

$$\begin{aligned}
&v_I - c + V(p_2) < v_1 - c + V(p_1)\\
&V_A(b_A) < v_1 - c + V(p_1)
\end{aligned}$$

Proof of the Proposition. Observe first that while $v_I - c + V(p_2)$ is independent of the value of v_1, all of the other values are dependent on v_1. The main intuition of the result is that the value of implementing early is increasing linearly in v_1:

$$\frac{\partial}{\partial v_1}\left(v_1 - c + V(p_1)\right) = 1$$

while the value of the other value functions are increasing at a slower rate:

$$\frac{\partial}{\partial v_1} V_A(b_A), \frac{\partial}{\partial v_1} V(b_{A,B}) < 1$$

This observation immediately gives us that region NR precedes all others, and that region II succeeds all others.

Moreover, note that $V_A(b_A)$ may experience a discontinuity, if the region shifts from DI to CI. However, this discontinuity only works in the favour of the proposition, since it must be a downwards jump. This observation gives that CI succeeds DI.

To see that DI succeeds GU, observe that

$$\max_{\lambda} \frac{\lambda(v_1 + v_2 - c + V(p_2)) - C(\lambda)}{r + \lambda} > V(b_{A,B})$$

This completes the proof. □

Proof of Proposition 2. We split the proof into several sections.

Proof of (i). Recall that there are strategic complementarities. This means that as firm $-i$ increases its investment, it is optimal for firm i to increase its own investment.

Observe that at the first boundary (between GU and DI or CI), the value W_i^{-i} does not change: firms are indifferent between continuing or not at this region.

Hence it is sufficient to show that

$$W_i^i(GU) > W_i^i(DI), W_i^i(CI)$$

This is immediate, since competition weakly decreases firms' value. To see this:

$$V(b_{A,B}), V(p_1) < \max_{\lambda} \frac{\lambda(v_1 + v_2 - c + V(p_2)) - C(\lambda)}{r + \lambda}$$

Along the border of DI and CI, the reason for the jump is similar. The value of the lagging firm changes continuously at the border, but the leading firm is hurt because the threat of co-option is larger.

The final comparison is more nuanced.

$$W_i^i(II) = v_1 - c + V(p_1), \qquad W_i^{-i}(II) = V(p_1)$$
$$W_i^i(CI) = V_A(b_A), \qquad W_i^{-i}(CI) = V_B(b_A)$$

As v_2 increases, the relative difference between $W_i^i(II)$ and $W_i^{-i}(II)$ decreases, while it does not decrease in region CI. To see this, recall that at the border between the two regions, $v_1 - c + V(p_1) = V_A(b_A)$.

This means that the free-riding incentive in region II becomes more pronounced as v_2 increases, while it does not in region CI.

Proof of (ii). The comparisons for region GU are immediate. Here, there is no competition, and so strategic complementarities do not encourage investment.

The final comparison comes from a similar reason. When v_2 is sufficiently small, the threat of appropriation drives investment in CI high. When v_2 is large, however, the threat of appropriation is large, strategic complementarities dominate.

The middle comparison is two-fold. First, the risk of appropriation is lower. For the leading firm:

$$W_i^i(DI) = W_i^i(CI), W_i^{-i}(DI) > W_i^{-i}(CI)$$

The reason this extends to the lagging firm is do to strategic complementarities: the leading firms' investment is larger, so the lagging firm also increases their investment.

Proof of (iii). The first comparison is straightforward:

$$W_i^i(DI) > W_i^i(CI), W_i^i(II), W_i^{-i}(DI) = W_i^{-i}(CI), W_i^{-i}(II)$$

The second comparison comes from the presence of competition and strategic complementarities. □

Proof of Proposition 3. As before, we proceed by proving each separately.

Proof of (i). The latter comparison is immediate. The former comparison in state b_i comes from the lack of competition. In state b_n this comes from $W_i^i(GU) > W_i^i(DI)$, and $W_i^{-i}(GU) = W_i^{-i}(DI)$.

Proof of (ii). Consider first the comparison between $V_{i,DI}(b_i)$ and $V_{i,CI}(b_i)$. W_i^i is the same in both of these regions. However, W_i^{-i} is lower in region CI. Since as well investment of the lagging firm increases (from Proposition 2), the value must be lower.

In state b_j, the comparison is similar. We have W_i^i equal across the two regimes, by indifference of the lagging firm. Additionally, we have $W_i^{-i} = V(p_2)$ in both regions. However, the leading firm has increased its investment due to the threat of appropriation. This means that the value is smaller.

Finally, in state b_n, since both W_i^i and W_i^{-i} are smaller, the value of firms must be smaller. This completes the proof. □

A.3 Proofs for Section 4

Proof of Proposition 4.

Proof of (i). The effect within regions is clear. Consider the equation that defines a firms' investment:

$$(r + \lambda_i + \lambda_{-i})\alpha C'(\lambda_i) - \alpha C(\lambda_i) = rW_i^i + \lambda_{-i}\left(W_i^i - W_i^{-i}\right)$$

The right-hand side is decreasing in α, since increasing α decreases the value of investment in the future. Additionally, the left-hand side is increasing in α. These together imply that if α decreases, then equilibrium investment must increase within regions.

Proof of (ii). To see that region NR shrinks, observe that since $v_1 + v_2 - c > v_I - c$ in order to work on the radical innovation, investment for A in state b_A is higher than in state p_2. Hence, decreasing α increases $\max_\lambda \frac{\lambda(v_1+v_2-c+V(p_2))-C(\lambda)}{r+\lambda}$ by more than it increases $V(p_2)$. Similarly for $V(p_1)$.

To see that region II shrinks, that investment is higher in state b_A than in state p_1. This implies that the dominating effect of α is for the leading firm to delay implementation. Since $v_1 - c + V(p_1) = V_A(b_A)$ at this border, this implies that this is the only relevant force.

Finally, to see that region DI expands, at both the border between it and GU and at the border between it and CI, investment is higher in this region because of Proposition 2. So, a decrease in α affects more region DI, expanding its boundaries.

□

Proof of Proposition 5.

Proof of (i). This is straightforward: increasing c_p decreases the value of every success, decreasing investment.

Proof of (ii). This is the analogue of the proof of Proposition 4. Delayed publication means fewer c_p, and later c_p. So, an increase in c_p has the smallest effect on DI, and the largest effect on II, NR. □

Proof of Proposition 6.

Proof of (i). Since decreasing α places emphasis on the deep story, there are no losses in decreasing α from changes in regions.

Since decreases in α also increase investment, there are intensive gains that come from decreasing α. Hence, it is optimal to set $\alpha \approx 0$.

Proof of (ii). When $v_2 < v_I$ and v_1 is sufficiently high, the equilibrium will be in region II. In this region, firms will never complete the radical innovation. Hence, c_p must be large enough to shift firm behaviour to DI. As v_1 grows, the value of c_p necessary for this also increases.

Then v_1 is sufficiently low, the dominating force is firms choosing to opt-out of the race for the radical innovation. This requires a high c_p to shift firms from either NR to GU or GU to DI. The necessary c_p to create this shift decreases as v_1 increases, since increasing v_1 makes both firms more likely to pursue the radical innovation, even if they are lagging.

□

Proof of Proposition 7. Fix v_I, α, β, r and $c_{p,T}$. For each publishable deep-story object $S \in \{1, 2, 12\}$ with $v_{12} \equiv v_1 + v_2$, the copier enters after publication of S if and only if

$$\beta v_S > c_{p,C}.$$

When the copier enters, it appropriates a fraction β of the gross publication payoff. Hence the traditional firm's effective payoff from publishing S is

$$\pi_S(c_{p,C}) := \left(1 - \beta \mathbb{1}\{\beta v_S > c_{p,C}\}\right) v_S - c_{p,T}.$$

Since $c'_{p,C} < c_{p,C}$, we have

$$\pi_S(c'_{p,C}) \leq \pi_S(c_{p,C}) \qquad \text{for all } S \in \{1, 2, 12\}.$$

The inequality is strict exactly for those S such that

$$c_{p,C} > \beta v_S > c'_{p,C}.$$

By contrast, the simple-story payoff

$$\pi_I = v_I - c_{p,T}$$

is unaffected by $c_{p,C}$.

Part (i). The value of choosing the simple story is unchanged. If the marginal firm focusing on the deep story is in the GU region, its value V depends on v_1 and v_2 only indirectly through π_{12}. The latter is

$$\left(1 - \beta \mathbb{1}\{\beta(v_1 + v_2) > c_{p,C}\}\right)(v_1 + v_2) - c_{p,T},$$

which decreases in $c_{p,C}$. Then, the result follows from V being strictly increasing in π_{12}.

If, otherwise, the marginal focusing on the deep story is in the II region, the relevant boundary is $v_1\left(1 - \beta \mathbb{1}\{\beta v_1 > c_{p,C}\}\right) = v_I$, which expands from $v_1 = v_I$ to $v_1 = v_I(1-\beta)^{-1}$ if $c_{p,C}$ decreases from $c_{p,C} > \beta v_1$ to $c'_{p,C} < \beta v_1$.

Part (ii). Suppose

$$c_{p,C} > \beta(v_1 + v_2) > c'_{p,C} > \beta \max\{v_1, v_2\}.$$

Then lowering $c_{p,C}$ induces copying of the bundled deep story, but not of either intermediate component. Hence

$$\pi_{12}(c'_{p,C}) = (1-\beta)(v_1 + v_2) - c_{p,T} < v_1 + v_2 - c_{p,T} = \pi_{12}(c_{p,C}),$$

while

$$\pi_1(c'_{p,C}) = \pi_1(c_{p,C}), \qquad \pi_2(c'_{p,C}) = \pi_2(c_{p,C}).$$

Therefore copier entry lowers the payoff from delayed bundled publication but leaves the payoff from separate publication unchanged. At the margin, firms substitute delayed publication with early publication.

Part (iii). Suppose first that

$$\beta(v_1 + v_2) > c_{p,C} > \beta \max\{v_1, v_2\}.$$

Then the bundled story is copied, but neither intermediate component is copied. Hence early publication prevents expropriation as explained above.

Now suppose the decrease in copier publication costs induces copying of component i:

$$c_{p,C} > \beta v_i > c'_{p,C}.$$

Then

$$\pi_i(c'_{p,C}) = (1-\beta)v_i - c_{p,T} < v_i - c_{p,T} = \pi_i(c_{p,C}).$$

The payoff from publishing component i separately falls, while the bundled payoff was already reduced by copier entry before the decrease. Therefore the appropriability gain from unbundling falls. Equivalently, early publication no longer protects the firm from copier expropriation of component i. Hence the incentive to publish early in order to avoid copier expropriation falls. At the margin, firms substitute early publication with delayed publication.

Finally, if $i = 2$, then the payoff from completing and publishing the second component after the first component has already been published falls. Therefore the continuation value in state p_1 falls relative to the value of switching to the simple story. Hence the set of parameters for which firms halt research after intermediate publication expands. Specifically, while research is halted following early publication for $v_2 < v_I$ before the decrease in publishing costs, it does so for $v_2 < v_I(1-\beta)^{-1}$ afterwards. □

B A Model With Secret Breakthroughs

This appendix studies a variant of the benchmark model in which breakthroughs are privately observed. We will show how the characterization of symmetric Markov Perfect Equilibria changes when firms no longer observe each other's progress on the radical innovation, and to verify that the main economic forces remain unchanged.

B.1 Modified Information Structure

The primitives are as in the benchmark model. The only change is informational: when a firm achieves the first breakthrough of the radical innovation, this event is not observed by its competitor unless the firm implements the breakthrough. We also assume that firms cannot observe investment decisions of others which would allow them to infer whether they have achieved a breakthrough.

Let $\mu_j(t) \in [0,1]$ denote the public belief that firm j has achieved the first breakthrough on the deep story at time t, conditional on not having published. The state is now given by $(\mu_i(t), \mu_j(t))$ together with the public outcome states f and b.

Firms have private information about their own breakthrough status. As a result, strategies depend on both time and beliefs, and beliefs evolve endogenously.

Fix effort policies $\lambda_{0,j}(t)$ (pre-breakthrough), $\lambda_{1,j}(t)$ (post-breakthrough), a pre-breakthrough focus policy $e(t)$, and publication intensity $P_j(t)$.[19] In the absence of public signals, beliefs evolve deterministically according to Bayes' rule:

$$\dot{\mu}_j(t) = (1-\mu_j(t))\left[e(t)\lambda_{0,j}(t) - \mu_j(t)\left(\lambda_{1,j}(t) + P_j(t)\right)\right]. \tag{1}$$

The first term reflects the arrival of new first-stage breakthroughs among firms that have not yet achieved one. The second reflects the fact that, conditional on no implementation, higher values of λ_1 or R make the absence of a public event more informative.

Importantly, $\dot{\mu}$ will be strictly increasing for t close to zero in any equilibrium where the radical innovation is pursued. By continuity, equilibrium beliefs then evolve increasingly until implementation or a steady state belief $\mu^* > 0$ is achieved.

B.2 Value Functions

Let $V(p_1)$ and $V(p_2)$ denote the continuation values from the benchmark public states in which the first breakthrough of the radical innovation has been implemented and in which the full radical innovation has been implemented, respectively. These states are public, so their values are the same as in the benchmark model.

[19] In the benchmark model implementation is a binary choice $p \in \{0,1\}$; here the stochastic rate $P(t)$ is a convenient way to describe mixed or interior implementation behavior.

When breakthroughs are hidden, the pre-implementation part of the problem is belief-dependent. Suppressing firm subscripts in symmetric equilibrium, denote the value of a firm with and without the first breakthrough as $V_0(\mu)$ and $V_1(\mu)$ respectively.[20] The former satisfies

$$\begin{aligned} rV_0(\mu) = \mu & \left[\lambda_{1,-i}(\mu)(V(p_2) - V_0(\mu)) + P_{-i}(\mu)(V(p_1) - V_0(\mu))\right] \\ & + e_i(\mu)\lambda_{0,i}(\mu)(V_1(\mu) - V_0(\mu)) + (1 - e_i(\mu))(v_s - c_p) - \alpha C(\lambda_{0,i}(\mu)) \\ & + \frac{\partial}{\partial \mu} V_0(\mu) \left[(1-\mu)\left[e_{-i}(\mu)\lambda_{0,-i}(\mu) - \mu\left(\lambda_{1,-i}(\mu) + P_{-i}(\mu)\right)\right]\right] \end{aligned}$$

where the first line captures the impact of the other firm's behaviour, the second line that of own breakthroughs, and the last line the impact of the deterministic change in beliefs.

Similarly, the value of a firm with the first breakthrough satisfies

$$\begin{aligned} rV_1(\mu) = \mu & \left[\lambda_{1,-i}(\mu)(V(p_2) - V_1(\mu)) + P_{-i}(\mu)(V(p_1) - V_1(\mu))\right] \\ & + \lambda_{1,i}(\mu)(V(p_2) - V_1(\mu)) + P_{1,i}(\mu)(v_1 - c_p + V(p_1) - V_1(\mu)) - \alpha C(\lambda_{1,i}(\mu)) \\ & + \frac{\partial}{\partial \mu} V_1(\mu) \left[(1-\mu)\left[e_{-i}(\mu)\lambda_{0,-i}(\mu) - \mu\left(\lambda_{1,-i}(\mu) + P_{-i}(\mu)\right)\right]\right] \end{aligned}$$

Optimal choices follow from writing the analogous HJB equation with an appropriate max operator. This makes it clear that the main forces remain unchanged, with the only difference that firms give-up and publication decisions are no longer discrete.

B.3 Equilibrium Behaviour and Steady-State Beliefs

The hidden-breakthrough model has the same economic regimes as the benchmark model, but the deterministic regions GU and CI become stochastic belief-driven regions. We use the following terminology.

Definition 3. In the hidden-breakthrough model, equilibrium behavior is classified as follows:

- "Never Radical" (NR): firms do not research the radical innovation.
- "Stochastic Giving-Up" (SG): firms initially research the radical innovation,

[20] Note that we can drop the time variable since beliefs evolve deterministically.

but as beliefs rise, firms without a breakthrough eventually mix between radical and incremental innovation.

- "Delayed Implementation" (DI): firms research the radical innovation and never implement the first breakthrough alone.
- "Stochastic Implementation" (SI): firms research the radical innovation and, once beliefs reach an interior steady state, firms with a first breakthrough implement it at a positive finite rate.
- "Immediate Implementation" (II): firms implement the first breakthrough immediately upon obtaining it.

The interpretation is close to the benchmark model. Region DI corresponds to delayed implementation. Region II corresponds to immediate implementation. Region GU is the analogue of the benchmark give-up region, except that firms do not observe whether they have fallen behind; instead, rising beliefs gradually reduce the value of continuing on the radical innovation. Region SI is the analogue of catching-up implementation: implementation occurs only after beliefs have risen enough to make firms with a breakthrough indifferent between implementing and waiting.

We can show that, given parameters v_I, c_p, α, r and (v_1, v_2), any symmetric equilibrium belongs to the five regions in Definition 3.

Since beliefs eventually converge to a unique steady-state value

$$\mu^* = \frac{e(\mu^*)\lambda_0(\mu^*)}{\lambda_1(\mu^*) + P(\mu^*)}.$$

we can solve for the stationary equilibrium as in the benchmark model.[21] However, unlike the benchmark model, it is not straightforward to solve the model through backward induction since it requires solving a system of differential equations. This adds an additional layer of complexity preventing closed-form solutions and general statements.

[21] Note how the stochastic give-up and publication rates ensure beliefs stay constant over time.

B.4 Equilibrium Focus and Publishing Decisions

We illustrate the results for focus and implementation decisions in Fig. 3 for the quadratic cost case. We observe that the regions closely resemble the behaviour in the benchmark model, with higher v_1 incentivizing focusing on the radical innovation, not giving up, and early implementation.

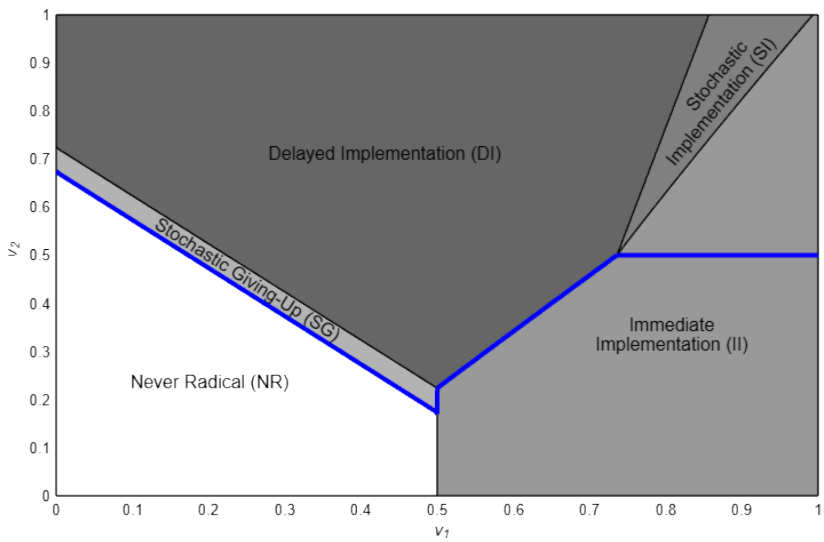

Figure 3: Equilibrium regions when breakthroughs are hidden, for the same parameter values as in Fig. 1.