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Author

Gilbert, RJ

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Competition, Mergers, and R&D Diversity

Richard J. Gilbert¹

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Abstract

This paper describes a model of research and development (R&D) investment in which firms can choose any number of R&D projects that have independent and identical probabilities of success. The measure of R&D diversity is the number of projects that are undertaken by the industry. Absent spillovers or profits at risk from innovation, mergers often—but not always—decrease R&D diversity; however, the incremental effects decline rapidly with the number of industry rivals. Mergers can have significant adverse effects if the merging firms have large profits that are at risk from an innovation. A merger can promote investment in R&D and increase expected consumer surplus if discoveries have sufficiently large information spillovers.

Keywords Competition · Innovation · Oligopoly · Mergers · Research and development

1 Introduction

Almost all merger challenges in research-intensive industries by U.S. antitrust agencies include allegations of harm to innovation (Gilbert and Greene 2015). However, economic research that relates mergers to innovation incentives has been limited until recently. Letina (2016), Salinger (2016), Federico et al. (2017, 2018), Motta and Tarantino (2017), and López and Vives (2018) show that mergers can have unilateral effects for investment in research and development (R&D) that are conceptually similar to the unilateral effects from mergers for price competition.¹

¹ The Horizontal Merger Guidelines published by the U.S. Department of Justice and Federal Trade Commission describe at a general level how unilateral effects from a merger can suppress innovation (United States Department of Justice and Federal Trade Commission 2010).

✉ Richard J. Gilbert
rjgilbert@berkeley.edu

¹ Department of Economics, University of California, Berkeley, 593 Evans Hall,
Berkeley 94720-3880, CA, USA

This paper extends the analysis in Federico et al. (2017, 2018) in several respects:

1. The model employed in this paper does not impose diseconomies of scale at the firm level in R&D. A firm can choose any number of R&D projects at a constant incremental cost.
2. The model shows that mergers can increase the probability of discovery in some circumstances.
3. The model allows for “replacement effects” described by Arrow (1962) that can reduce firms’ incentives to invest to develop new products or reduce costs.
4. The model also allows for information spillovers that can reduce industry R&D incentives.

Absent spillovers, the model shows that mergers often—but not always—reduce industry R&D effort and the probability of discovery. In addition, adverse price effects from mergers can harm consumers even if mergers increase innovation incentives. Mergers can promote innovation and expected consumer surplus if technological spillovers benefit imitators or enable follow-on innovations.

2 R&D Diversity and the Cost of Innovation

The effects of competition on innovation depend on how rivalry affects the incentives to invest in R&D and its costs. Papers that examine these effects typically assume R&D cost functions that have decreasing returns to R&D investment at the firm level. Modeling innovation incentives with the use of cost functions that exhibit decreasing returns confounds the effects of greater rivalry on incentives to invest in R&D with the effect of greater rivalry on the cost of R&D.

For example, consider an extreme case in which firms can profitably undertake only a single R&D project. It follows that if every firm invests in a project, greater rivalry increases R&D diversity and the likelihood of innovation. Perhaps this logic motivated Hoven and Rubinfeld (2001) to suggest that antitrust policy should preserve a large number of firms in an industry to maintain adequate diversity of R&D effort. Similarly, Comanor and Scherer (2013) attribute a decline in the productivity of pharmaceutical innovation to the loss of “parallel R&D paths” from mergers.

However, it is unclear why R&D investment should exhibit decreasing returns to scale at the firm level if firms can replicate R&D programs in-house without sacrificing efficiencies.² I derive a condition under which R&D cost functions exhibit decreasing returns to scale. I then introduce a R&D cost function that does not have this property and explore its implications for the effects of competition and mergers on innovation incentives.

Following Federico et al. (2017, 2018), firms can invest in R&D to discover a new product, such as a new drug to treat Alzheimer’s disease. Each firm has a cost function $c(p)$ that relates R&D expenditures to the firm’s probability of success: p .

² For example, firms can create “skunkworks” that replicate R&D that might have occurred in a different organization. Gans (2016) discusses the costs and benefits of such strategies.

If an industry has R symmetric R&D rivals—each of which has success probability p —the probability that at least one firm makes a discovery is

$$Y = 1 - (1 - p)^R. \quad (1)$$

The cost of achieving the industry success probability Y is

$$C(Y) = Rc(p). \quad (2)$$

If we hold Y constant, Eq. (1) determines the relationship between p and R , which in turn determines $C(Y)$ from Eq. (2). For a given value of Y , minimizing industry-wide total R&D costs involves a tradeoff between investing in R&D at the firm level to increase p or increasing the number of firms R that are engaged in R&D. The latter strategy is more efficient if, holding Y constant, the right-hand-side of Eq. (2) is decreasing in R . R&D cost functions exhibit decreasing returns to scale at the firm level if this condition is satisfied.³

Industry R&D costs $C(Y)$ would not depend on R if firms can efficiently replicate “parallel R&D paths” in-house. In that case, harm to innovation from a reduction in rivalry must come from a reduction in firms’ incentives to invest in R&D and not because fewer firms that are engaged in R&D increases the cost of discovery.

Following Sah and Stiglitz (1987), suppose that firms can invest in any number of projects, each of which has a fixed cost, k , that does not depend on the total number of investments.⁴ Individual projects have an identical and independent probability of success, p , and a probability of failure $q = 1 - p$.

Let $N(Y)$ be the number of projects that are required to achieve a discovery probability Y . Since $Y = 1 - q^N$, then

$$N(Y) = \frac{\ln(1 - Y)}{\ln(q)}.$$

If each project has a fixed cost k , the cost of achieving the discovery probability Y is

$$C(Y) = kN(Y) = k \frac{\ln(1 - Y)}{\ln(q)}.$$

This cost function implies that R&D has decreasing returns to scale at the industry level: $C'(Y) > 0$ and $C''(Y) > 0$. However, there are no diseconomies of scale conditional on Y . The cost of achieving an industry discovery probability Y depends only on the total number of projects that are undertaken by all firms— $N(Y)$ —and not on whether the projects are undertaken by a single firm or by several firms.⁵

³ The cost function in Federico et al. (2018) has the property that—holding Y constant— $Rc(p)$ is decreasing in R .

⁴ Letina (2016) has a related approach that examines projects as selections from available portfolios of R&D investments.

⁵ Section 5 describes economies or diseconomies of scale that might arise from mergers or from correlations between project outcomes. Denicolò and Polo (2018) provide an example in which a merged firm can reallocate R&D investments to increase the probability of success for a given expenditure compared to independent rivals. That does not arise in this model because project success probabilities are independent of R&D effort.

The next section describes the equilibrium investments by firms that can invest in any number of projects with no diseconomies of scale at the firm level. Section 4 addresses welfare effects from mergers. In the base case that is described below, firms have no profits that are at risk from innovation, and there are no informational spillovers that can benefit imitators. Section 5 relaxes these assumptions. Although generally the incentive effects for R&D from a merger are not comparable to the effects from one less rival, they are identical in the base case. Departures from the base case can break the equivalence between a merger and a reduction in the number of firms in a symmetric oligopoly. For example, if firms sell differentiated products, a merger would create an asymmetry in payoffs because the merged firm can coordinate prices for the merging parties' products.

3 Equilibrium R&D Diversity with Constant Returns to Scale at the Firm Level

An industry has R symmetric rivals that invest in R&D projects. Firms have no current profits and can invest in any number of R&D projects, each of which has a fixed cost: k . Projects succeed with an independent probability p and fail with probability $q = 1 - p$. Let $\pi(j)$ denote the profit that a firm would earn if it is one of j innovators. The probability that j rivals have at least one success when each firm invests in n R&D projects is

$$P(j, R-1, n) = \frac{(R-1)!}{j!(R-1-j)!} q^{n(R-1-j)} [1 - q^n]^j \text{ for } j = 0, \dots, R-1. \quad (3)$$

Firm i 's expected profit from n_i R&D projects is⁶

$$(1 - q^{n_i}) \sum_{j=0}^{R-1} P(j, R-1, n) \pi(j+1) - n_i k. \quad (4)$$

The term preceding the summation is the probability that at least one of Firm i 's projects succeeds, and the summation measures the firm's expected payoff conditional on its success and on the number of rivals that also make discoveries.

The analysis assumes that R&D projects are divisible. Firms can invest in, say, 3.5 projects, which reflects an allocation of effort that is greater than three but less than four projects.⁷ Furthermore, R&D costs are not sunk. Consequently, equilibrium R&D investments do not depend on any initial configuration of firm investments.

In an interior symmetric equilibrium, each firm chooses the number of R&D projects n for which

⁶ This formulation assumes that the firm commits in advance to invest in n_i projects and does not observe any R&D outcomes before it invests. If the firm could invest conditional on its project realizations, the firm would invest in another project only if its other projects failed and if $p \sum_{j=0}^{R-1} P(j, R-1, n) \pi(j+1) > k$.

⁷ Divisible and non-divisible investment can be reconciled by equating a non-divisible project with success probability p to a bundle of t independent projects, each of which has success probability $\bar{p} = 1 - (1 - p)^{1/t}$. The bundle represents divisible investment in the limit as $t \rightarrow \infty$.

$$-\ln(q)q^n \sum_{j=0}^{R-1} P(j, R-1, n)\pi(j+1) = k, \quad (5)$$

and the probability that at least one firm makes a discovery is $Y(R) = 1 - q^{nR}$.

Suppose that Firms 1 and 2 merge. If there are no profits at risk from innovation, the post-merger industry is also symmetric with $R-1$ firms. In this case a merger presents the same incentives for R&D investment as does a reduction in rivalry by one firm. The merged firm's optimization problem is identical to those of its $R-2$ rivals and there is a post-merger equilibrium in which each of the $R-1$ firms invests at the same level.

The following proposition describes some useful properties of this model.

Proposition 1 *Let $Y(R)$ be the probability of discovery in a symmetric oligopoly with R firms when the number of R&D projects is divisible and each R&D project succeeds with independent probability $p \in (0, 1)$. Let $\pi(j)$ be the payoff to each firm from discovery when j firms have successful R&D programs.*

- (i) *If $\pi(j) = 0$ for $j \geq 2$, then $Y(R) = Y(R')$ for any R, R' .*
- (ii) *If $\pi(R) = 0$ for $R > \bar{R}$, then $Y(R+1) \rightarrow Y(R)$ as $R \rightarrow \infty$.*

The proofs of this and other propositions are in the Appendix.

Sah and Stiglitz (1987) established the first part of Proposition 1. If a firm can profit from discovery only if it is the sole successful innovator, then the expected return from investing in R&D depends only on the total industry number of projects and not on the firms that invest in the projects. Because the incremental expected return from R&D is the same for any firm and depends only on the industry total number of projects, the profit-maximizing number of projects does not depend on the number of rivals. The number of profit-maximizing investments for a monopolist is the same as the total number of profit-maximizing investments for an industry with many competitors.

Reynolds and Isaac (1992) and Farrell et al. (2003) showed that this invariance result is not robust to the nature of product market competition. Greater rivalry generally increases the probability of discovery, but the second part of the proposition shows that if sufficiently intense rivalry forces profits to zero, the incremental effect of rivalry is small when the number of rivals is very large.

The next proposition extends a result in Federico et al. (2017) to the cost function in this paper.

Proposition 2 *A merger to monopoly decreases the probability of discovery if $\pi(2) > 0$; i.e., $Y(1) < Y(2)$*

A merger to monopoly reduces the probability of discovery if co-discovery has any positive expected payoff, although the magnitude of this effect can be small if the probability that R&D projects succeed is either very high or very low.

From Proposition 1, the industry discovery probability converges to a limiting value as $R \rightarrow \infty$ if $\pi(R) = 0$ for $R > \bar{R}$. However, the next proposition shows that

the industry discovery probability can reach a maximum value with a finite number of rivals:

Proposition 3 *Suppose that $\pi(1) = \pi$, $\pi(2) = \theta$ with $\theta \in (0, \frac{\pi}{2})$ and $\pi(j) = 0$ for $j > 2$. There exists a $R > 2$ and a failure probability $\tilde{q}(R) > 0$ such that $Y(R-1) > Y(R)$ if $q < \tilde{q}(R)$.*

Federico et al. (2017) assume a convex increasing relationship between R&D effort and discovery and show that if $\pi(j) = 0$ for $j > 2$, then in the limit as $\pi(2)$ approaches zero, a merger increases total industry expenditures on R&D if R is sufficiently large.⁸ Proposition 3 modifies this result in two ways. First, the Proposition shows that a merger can increase the probability of discovery in addition to increasing R&D expenditures given the assumed R&D cost function. Second, Proposition 3 is not restricted to the limiting case in which $\pi(2) \rightarrow 0$.

The profit assumption in Proposition 3 corresponds to “modified Bertrand” competition in which a firm earns a fraction θ of monopoly profits if it is one of two successful innovators but nothing if it is one of three or more successful innovators. With modified Bertrand competition, an increase in the number of rivals can create a large “congestion effect” that reduces expected profits if R&D projects have a high probability of success (q is small).

The congestion effect occurs because an increase in the number of rivals reduces the probability that a firm is either the sole inventor or one of two successful inventors. With modified Bertrand competition, these are the only outcomes for which the firm has a positive payoff from invention. As a result, competition can reduce the expected return from R&D by enough to more than offset the benefit from having an additional R&D competitor. In that case a merger can increase the probability of discovery.

The practical significance of the congestion effect for merger policy is limited for two reasons. First, it arises only when projects have high success rates, which implies that the probability of discovery is high even if competition reduces total industry R&D investment. Consequently, a merger would have only a small effect on the probability of discovery. Second, when innovators’ products are substitutes, competition among successful inventors benefits consumers by reducing expected prices. A merger would deprive consumers of these benefits from price competition even if it increases the probability of discovery.

⁸ Proposition 2 in Federico et al. (2017) states that total industry R&D effort falls following a merger if, but only if, the number of rivals is below a critical number.

4 R&D Competition, Price Competition, and Welfare

The model predicts that for most reasonable parameter values mergers reduce total R&D investment and reduce the probability of discovery. This section explores the impact of the change in R&D investment on consumers.

Let $S(j)$ be the realized consumer surplus if j firms innovate, and let $W(R)$ be the expected consumer surplus from innovation in a symmetric industry with R rivals, each of which has n R&D projects:

$$W(R) = \sum_{j=1}^R P(j, R, n)S(j),$$

where $P(j, R, n)$ is given by Eq. (3).

A candidate statistic to measure the effect of a merger is the percentage change in expected consumer surplus: $\frac{\Delta W(R)}{W(R)} = \frac{W(R-1) - W(R)}{W(R)}$. This statistic measures two effects: (1) the harm from the reduction in the probability of discovery and (2) the harm from the loss of future price competition. The latter effect can be large, but it is not the focus of this paper, which is the effect of a merger on innovation competition.

An alternative statistic is the percentage change in the probability of discovery: $\frac{\Delta Y(R)}{Y(R)} = \frac{Y(R-1) - Y(R)}{Y(R)}$. However, this statistic can be a misleading indicator of innovation effects from a merger. It is close to zero if $Y(R)$ and $Y(R-1)$ are close to one. If $Y(R)$ and $Y(R-1)$ are small, the harm from a merger is also small, but the percentage change in the probability of discovery can be large.

Innovation-related harm from a merger reaches a maximum value at intermediate values of $Y(R)$ for which $\Delta Y(R) = Y(R-1) - Y(R)$ is large. This section explores the effects of mergers on both the percentage change in the probability of discovery and the percentage change in consumer surplus when $\Delta Y(R)$ is near its maximum value.

It is useful to normalize profits and project costs to avoid inferences that are driven solely by absolute values. Toward that end, let V be the maximum total economic surplus from the innovation, which corresponds to marginal cost pricing. Let $\pi(j) = V\theta(j)$. Then we can re-write Eq. (5) as

$$-\ln(q)q^n \sum_{j=0}^{R-1} P(j, R-1, n)\theta(j+1) = \frac{k}{V} \equiv \beta. \quad (6)$$

This expression allows us to study how competition influences R&D incentives by focusing on the relative profits $\theta(j)$ and the normalized R&D project cost: β . Given $\theta(j)$, the value q^* for which $\Delta Y(R)$ is a maximum depends on β . However, conditional on q^* , simulations indicate that different values for β have little effect on $\Delta Y(R)$ or on the percentage change in $Y(R)$ or $W(R)$ from a merger.

To address the effects of mergers on expected consumer surplus, first assume that successful innovators behave as symmetric Nash-Cournot competitors and

supply a homogeneous product with linear demand. Let $t(j)$ be the equilibrium price with j innovators. At price $t(j)$, demand is $Q = a - bt(j)$ with $a > 0$ and $b > 0$. The discovery has a constant marginal production cost, c , and there is no existing product or production technology that is at risk from innovation.

The maximum total economic surplus from the innovation that corresponds to marginal cost pricing is $V = \frac{1}{2b}(a - bc)^2$. Let q_i be Firm i 's output. Each successful innovator chooses q_i to maximize $\pi_i = q_i(t(j) - c)$. Profit-maximization implies that if j firms make a discovery and there are no profits from an existing technology, each innovating firm earns a profit

$$\pi(j) = 2V \left(\frac{1}{j+1} \right)^2,$$

and consumers have aggregate surplus

$$S(j) = V \left(\frac{j}{j+1} \right)^2.$$

Figure 1 shows the percentage reduction in the probability of discovery ($\Delta Y(R)/Y(R)$) and in expected consumer surplus ($\Delta W(R)/W(R)$) from a merger in a symmetric oligopoly with no profits at risk when $\beta = 0.025$ and the project success probability is $p = 0.10$.⁹ The success probability is close to the value that maximizes $\Delta Y(R)$, and for each value of R , each firm invests in the number of R&D projects $n(R)$ that is the solution to Eq. (5).

A merger is equivalent to reducing the number of firms from R to $R - 1$ in this example because payoffs depend only on the number of rivals. A four-to-three merger reduces the probability of discovery by about three percent.¹⁰ More competitors increase the probability of discovery but the incremental effect from another rival is small in a market with several competitors.

Consumer harm from a merger comes from both a reduction in the probability of discovery and a reduction in future price competition conditional on discovery. The relative contributions from these two sources of harm depend on the project success probability p . The loss of future price competition accounts for a large fraction of the loss of expected consumer surplus if R&D projects have a high probability of success. In Fig. 1, the loss of price competition accounts for more than half of the reduction in consumer surplus from a four-to-three merger.

Two examples of industry competition bracket the Nash–Cournot model. At one extreme, suppose that innovators coordinate prices for the new product and share profits at the monopoly price $t^m = \frac{1}{v^{2b}}(a + bc)$. In this case, each firm's profit if j firms make the discovery is $\pi(j) = \frac{1}{2j}$. With coordinated prices an increase in rivalry

⁹ Note that the percentage reduction in the discovery probability and in consumer surplus is independent of V given β .

¹⁰ The probability of discovery falls from 69.5% with four firms to 67.3% with three firms.

Fig. 1 Percent reduction in the discovery probability and consumer surplus from merger: R to $R-1$ in a symmetric Nash–Cournot oligopoly. (Linear demand; $p=0.10$; $\beta=0.025$)

has a greater impact on innovation incentives relative to the case with Nash–Cournot competition and, conversely, a merger has a larger negative effect on the probability of discovery. For the parameter values that are assumed in Fig. 1, the probability of discovery increases from about 52% in a monopoly to about 72% in an industry with seven symmetric Nash–Cournot competitors. If instead innovators coordinate on the monopoly price, the discovery probability increases to about 77% with seven firms.

The effect of a merger on expected consumer surplus equals its effect on the probability of discovery when innovators set the price of a discovery collusively. With Nash–Cournot competition, expected consumer surplus with seven R&D rivals is roughly twice the expected consumer surplus from a monopoly given the parameter values in Fig. 1.¹¹ With price collusion, an industry with seven rivals increases expected consumer surplus by less than 50 percent compared to a monopoly.

At the other extreme, suppose that innovators act as Nash–Bertrand competitors that sell a homogenous product with the same constant marginal production cost. Competition eliminates profits if two or more firms innovate. From Proposition 1, the number of firms in the industry that invest in R&D has no effect on the probability of discovery: nR is independent of R . But rivalry (measured by the number of firms that invest in R&D) has a large effect on expected consumer surplus. Greater rivalry increases the probability that two or more firms innovate. Competition between two or more innovators drives the price of the innovation to its marginal production cost, which has large consumer benefits.

¹¹ This ratio exceeds the cumulative effects on expected consumer surplus shown in Fig. 1 because the figure shows the reduction in surplus from a merger rather than the increase in surplus from greater competition.

5 Replacement Effects, Technological Spillovers, and Correlated Returns

The preceding analysis assumes that a firm earns nothing if it does not innovate. Firms can earn a profit if they do not innovate because they have existing products that generate profits or because they can imitate innovations by their rivals. Profits from existing products that are at risk from innovation are the source of the replacement effect that was identified by Arrow (1962). Firms that imitate innovations can capture spillover benefits. Both the replacement effect and spillovers can reduce innovation incentives and confound the effects of mergers for innovation and consumer welfare.

5.1 Replacement Effects

The incentive to innovate is the difference between the profit that a firm would earn if it is a successful innovator and the profit it would earn if it does not innovate. Arrow (1962) showed that a firm's existing profits that would be replaced by an innovation reduce the firm's incentive to innovate. His analysis assumed that an innovation decreases marginal production costs but the intuition also applies to a new product that replaces an existing product.

Let $\pi_0(j, R)$ be a firm's profit from an existing product or production technology if it fails to innovate and $j=0, \dots, R-1$ other firms innovate. This is the profit from incumbency that is at risk from innovation. Let $\pi_1(j, R)$ be a firm's profit if it is one of j innovators, with $j=1, \dots, R$. Firm i 's profit-maximizing R&D effort maximizes

$$\sum_{j=0}^{R-1} P(j, R-1, n) [(1 - q^{n_i}) \pi_1(j+1, R) + q^{n_i} \pi_0(j, R)] - n_i k. \quad (7)$$

The first term in brackets is the probability that Firm i innovates, multiplied by its profit conditional on j other innovators. The second term in brackets is the probability that Firm i fails to innovate, multiplied by the profit that it earns from its existing product or production technology when j other firms innovate.

Firm i 's profit-maximizing investment solves

$$-\ln(q) q^{n_i} \sum_{j=0}^{R-1} P(j, R-1, n) [\pi_1(j+1, R) - \pi_0(j, R)] = k. \quad (8)$$

The replacement effect reduces Firm i 's expected incremental profit from R&D if $\pi_0(j, R) > 0$. A "drastic" innovation is one for which $\pi_0(j, R) = 0$ for $j \geq 1$. A firm that has only the existing legacy technology cannot compete with one or more rival innovators if the innovation is drastic.

The competitive significance of the replacement effect depends on the profits that are at risk from innovation and how they compare to the profit that a firm can earn by innovating. As in the base case, suppose that R rivals act as Nash–Cournot competitors for a homogenous product with linear demand $Q = a - bt$. Let $t(j, R)$ be the product

price with j innovators in a market with $R \geq j$ rivals. An innovation decreases the marginal production cost from c_0 to c_1 .

Define the weighted average marginal production cost

$$\bar{c}(j, R) = \frac{jc_1 + (R-j)c_0}{R}.$$

If all R firms have $q_i > 0$, which requires $t(j, R) > c_0$, then the equilibrium price with j innovators is

$$t(j, R) = \frac{1}{b} \left(\frac{1}{R+1} \right) [a + Rb\bar{c}(j, R)].$$

Let $z=1$ if Firm i is an innovator and $z=0$ otherwise. In an industry with j innovators, Firm i earns

$$\pi_z(j, R) = 2V_z(j, R) \left(\frac{1}{R+1} \right)^2,$$

where

$$V_z(j, R) = \frac{1}{2b} [a - b(c_z - R(\bar{c}(j, R) - c_z))]^2.$$

If $t(j, R) < c_0$, the innovation is drastic, in which case only the innovators are active. The j innovators earn

$$\pi_1(j) = 2V_1 \left(\frac{1}{j+1} \right)^2$$

with $V_1 = \frac{1}{2b} (a - bc_1)^2$, and the remaining $R-j$ firms earn zero.

Figure 2 reports the results of three scenarios that illustrate the consequences of the replacement effect for R&D investment and the probability of discovery. In each scenario, $a=20$, $b=1$, $c_1=0$, and $p=0.10$. The solid black bars correspond to zero profits at risk from discovery; hence, there is no replacement effect. This case repeats the Nash–Cournot equilibrium outcomes in the preceding section.

In the second scenario (the striped bars), $c_0=10$ and innovation is drastic: $\pi_0(j, R) = 0$ for $j \geq 1$. A firm earns a profit from the existing legacy technology only when no firms innovate. This has a large effect on R&D investment incentives and the discovery probability in highly concentrated industries but the effect diminishes rapidly with more rivals.

The third scenario illustrated in Fig. 2 (the dotted bars) corresponds to $c_0=6$, for which $\pi_0(j, R)$ is positive if $j=0, 1$, or 2 and zero if $j \geq 3$. The discovery probability is much lower in this scenario because the expectation of earning profits using the legacy technology creates a large disincentive for R&D investment. A firm that does not invent earns a higher profit and a firm that invents earns a lower profit when innovation is not drastic compared to the scenario with drastic innovation. Furthermore, the discovery probability exhibits an “inverted-U” dependence on the number of rivals in this example, and firms have no incentive to invest in R&D in an industry

Fig. 2 Discovery probability in a symmetric Nash–Cournot oligopoly with and without replacement effects. (linear demand; $a=20$; $b=1$; $p=0.10$; $\beta=0.025$)

with six or seven rivals. An efficient legacy technology can eliminate incentives for firms to invest in the new production technology.

The third scenario illustrates an appropriation effect. Competition from firms that employ the legacy technology reduces the payoff from innovating and, conversely, a reduction in competition can increase R&D incentives. Competition from firms that employ the legacy technology has no effect on appropriation if innovations are drastic.

In general, replacement effects break the equivalency between a merger and a reduction in the number of symmetric rivals from R to $R-1$. For example, if firms sell differentiated products, the merging firms would coordinate prices for their products. This would create an asymmetry between the merged firm and firms that do not merge and exacerbate the replacement effect by increasing the merged firm's profits from its legacy products.

A merger is equivalent to a reduction in rivalry in the special case illustrated in Fig. 2 for which the merging firms have the same legacy technologies, products are homogeneous, innovation is a reduction in marginal production cost, and firms compete as Nash–Cournot oligopolies. Mergers increase the probability of discovery for the third scenario in Fig. 2 except for a merger to monopoly. Nonetheless, mergers harm consumers in this scenario. When the industry has more than a few firms, the probability of discovery is low in this example, and market prices are determined primarily by competition among firms that use the legacy technology. Greater competition reduces prices and increases consumer surplus for the usual reasons.

The merging firms' existing products do not have to be substitutes for the replacement effect to reduce incentives to invest in R&D. It is the total profit at risk from innovation that affects investment incentives. For example, suppose a firm that manufactures an injectable form of insulin merges with another firm that manufactures a pump to administer the insulin. The products are complements, and combining the

two firms would have the efficiency benefits of the usual sort that relate to complementary products. However, if the merged firm is also a candidate for the discovery of an oral medication that would replace injectable insulin, the innovation would replace the profit streams that are associated with both the injectable insulin and the pump. The increased profits that are at risk from innovation from both existing complementary products would discourage post-merger R&D investment.

5.2 Spillovers

Spillovers allow firms to imitate discoveries that are made by others and in doing so reduce the profits earned by innovators. Although the magnitudes of information spillovers vary by technology and firm size, in the aggregate they are very large. Bloom et al. (2013) estimate that the average social rate of return to R&D—which includes spillover benefits that accrue to imitators—is two to three times as large as the average private rate of return.¹²

An extension of the two-period model of R&D diversity allows for spillovers. Spillovers do not affect monopoly innovation incentives because, absent new entry, the monopolist has no rivals that can benefit from information about the monopolist's products or production technologies. Consider $R \geq 2$. Suppose there are $j = 1, \dots, R - 1$ innovators and $f = R - j$ imitators. Let s index spillovers with $s \in [0, 1]$. Spillovers harm innovators and benefit imitators. A firm that is one of j innovators in a market with R rivals earns (with superscript “ l ” for “leader”) $\pi^l(j, R, s)$ with $\pi^l(j, R, 0) = \pi(j)$, $\pi^l(j, R, 1) = \pi(R)$, and $\frac{\partial \pi^l(j, R, s)}{\partial s} < 0$. An imitator earns (with superscript “ f ” for “follower”) $\pi^f(j, R, s)$ with $\pi^f(j, R, 0) = 0$, $\pi^f(j, R, 1) = \pi(R)$, and $\frac{\partial \pi^f(j, R, s)}{\partial s} > 0$. When $s = 1$, firms earn the profit that corresponds to innovation by the entire industry. Furthermore, if $j = R$ firms innovate, each firm earns $\pi(R)$.¹³

A firm can invest to be an innovator or merely follow innovations that are made by others. Firm i 's expected profit if it invests in n_i R&D projects is

$$\sum_{j=0}^{R-1} P(j, R-1, n) [(1 - q^{n_i}) \pi^l(j+1, R, s) + q^{n_i} \pi^f(j, R, s)] - n_i k. \quad (9)$$

Expression (9) parallels expression (7) for the replacement effect, with profits that a firm would earn as an imitator substituting for the profit that a firm would earn from its legacy products or technologies.

¹² Spillovers increase consumer surplus by promoting price competition and facilitating follow-on improvements in the innovator's industry. Spillovers also may benefit firms and consumers in other industries where a discovery adds value or advances innovation. As Spence (1984) observed, it is efficient to subsidize R&D in the presence of spillovers rather than to prevent them: for example, by strengthening patent rights.

¹³ These specifications assume that spillovers do not have cumulative effects that allow innovators to benefit from other innovators.

If $R \geq 2$, Firm i will choose the number of R&D projects n_i for which

$$-\ln(q)q^{n_i} \sum_{j=0}^{R-1} P(j, R-1, n)\Phi(j+1, R, s) = k,$$

where

$$\Phi(j+1, R, s) = \pi^l(j+1, R, s) - \pi^f(j, R, s) \text{ for } j = 0, \dots, R-2$$

is the difference between the profit from innovating and the profit from imitating and $\Phi(R, R, s) = \pi(R)$.

Spillovers can affect industry profits in different ways. Suppose that spillovers reallocate profits from innovators to imitators but do not lower the total profit from innovation. Each imitator earns a fraction s of the profit that the firm would earn if the entire industry possessed the innovation, weighted by the number of innovators:

$$\pi^f(j, R, s) = sj\pi(R) \text{ for } j = 0, \dots, R-1 \text{ and } f = 1, \dots, R-j. \quad (10)$$

Each innovator earns

$$\pi^l(j, R, s) = \pi(j) - sf\pi(R) \text{ for } j = 1, \dots, R \text{ and } f = R-j, \quad (11)$$

and total industry profit is $j\pi(j)$.

This specification reasonably assumes that imitators benefit from more innovators, and spillovers have a greater adverse effect on innovator profits, when the number of imitators is large. Note that $\Phi(j+1, R, s) = \pi(j+1) - sR\pi(R)$ can be negative if the spillover share is sufficiently large. This can give rise to a waiting game in which firms prefer to be imitators rather than innovators.¹⁴

Figure 3 illustrates how spillovers can change R&D incentives and the probability of discovery. The black bars in Fig. 3 show the probability of discovery as a function of the number of symmetric industry rivals in the base case Nash–Cournot model with no spillovers or replacement effects. The shaded bars show the probability of discovery when spillovers change payoffs according to the specification that is described in Eqs. (10) and (11) with $s=0.50$. In the presence of sufficiently large spillovers, total industry investment in R&D and the probability of discovery can be higher in a monopoly than in an industry with several rivals: A merger to monopoly can increase investment in R&D.

In the assumed specification—if we hold the number of innovators and the spillover share constant—if $R \geq 2$, an increase in the number rivals reduces the adverse effect of spillovers on innovation incentives because $R\pi(R)$ declines with R with Nash–Cournot competition and imitation does not reduce total profits from innovation.

Other reasonable specifications for spillovers could have some combination of: $R\pi(R)$ increasing with R ; a spillover share that increases with R ; or total profits that decrease with the number of imitators. These “wrinkles” can cause greater

¹⁴ Katz and Shapiro (1987) illustrate conditions under which firms play a waiting game when innovation benefits a rival.

Fig. 3 Discovery probability in a symmetric Nash–Cournot oligopoly with and without spillovers. (Spillovers are given by Eqs. (10) and (11); $s=0.5$; other parameter values are unchanged from Fig. 1)

rivalry to aggravate the negative incentive effects for innovation from spillovers. Along with the replacement effect for non-drastic innovation that is illustrated in Fig. 2, these types of spillovers can cause a merger to increase the probability of discovery.

Spillovers can benefit firms and consumers in different markets. The effect of a merger on total consumer surplus depends on its effect on surplus in the market in which the innovation occurs and its external effect on surplus in other markets. Let S_e be the total consumer surplus that is created from spillovers in markets other than the market in which the innovation occurs. Let $W(R)$ be the expected consumer surplus in the market with R rivals in which the innovation occurs, and let $Y(R)$ be the probability of discovery. The effect of a merger on total consumer surplus is:

$$\Delta W^{total}(R) = W(R-1) - W(R) + \Delta Y(R)S_e$$

where $\Delta Y(R) = Y(R-1) - Y(R)$.

The adverse effect of a merger on price competition typically implies that the merger reduces expected consumer surplus in the market in which the discovery occurs even if it increases the probability of discovery. Nonetheless, a merger that increases the probability of discovery can increase total surplus if external spillover benefits S_e are sufficiently large.

5.3 Correlated Returns

A relaxation of the assumption that R&D project outcomes are statistically independent does not change the qualitative nature of firms' investment decisions. An additional R&D project is profitable if its expected payoff—conditional on the failure of other projects—exceeds the project's cost. However, correlated project returns

have quantitative implications for the structure of firms' profit-maximizing R&D portfolios and for the effects of mergers on total R&D investment.

Consider an industry with two firms, and suppose that R&D outcomes are perfectly positively correlated. In a symmetric equilibrium each firm invests in n projects. Either both firms succeed with probability $1 - (1 - p)^n$, in which case they earn duopoly profits, or neither succeeds. If they merge and the merged firm invests in n' projects, it earns monopoly profits with probability $1 - (1 - p)^{n'}$. The merged firm would invest in no less than n projects if duopoly profits are significantly less than monopoly profits. Because the duopoly outcomes from the n projects are perfectly correlated, a merger can increase the expected probability of discovery in this example.

Suppose instead that the two firms' R&D outcomes are perfectly negatively correlated. Failure by one firm implies success for its rival. Pre-merger, suppose that both firms invest in n projects. A firm's R&D portfolio succeeds with probability $1 - (1 - p)^n$, in which case its rival fails and the firm earns a monopoly profit. Post-merger, the firm can invest in n projects from each of the merging parties' portfolios and earn a monopoly profit if either portfolio is successful. This can imply a greater incentive to invest post-merger if the pre-merger probability of success is not large.

The ability of the merged firm to increase the probability of successful R&D by investing in a diversified portfolio is a cognizable efficiency defense if comparable benefits cannot be achieved without the merger. These complementarities and related cost-savings from combining R&D operations can be a defense against arguments that a merger reduces innovation incentives if they cannot be achieved in the absence of the merger.

6 Conclusions

Innovation incentives depend on many factors, only some of which can be analyzed with a simple two-period economic model, such as the one in this paper. The model does not account for organizational limitations, financial constraints, or agency issues—all of which can have large impacts for innovation—and ignores the role of idiosyncratic creativity for invention.

The two-period model also does little to analyze the interactions between R&D incentives and the evolution of market structure and technological capabilities. Changes in competition can increase or decrease industry innovation rates by changing the composition over time of firms with different technical capabilities and different incentives to invest in R&D.¹⁵ With many time periods, firms may compete aggressively to gain an advantage over their competitors but then reduce R&D effort if they achieve technological superiority.¹⁶ Hence policies that promote competition

¹⁵ Gilbert et al. (2018) extend Aghion et al. (2001, 2005) to analyze the effects of rivalry in an oligopoly where firms can have different technological capabilities and must first catch up to their rivals before they can surpass them.

¹⁶ See, e.g., Fudenberg et al. (1983) and Vickers (1986).

in the short term can have adverse effects for innovation over a longer time horizon. Furthermore, if innovations are not drastic, incumbents with market power may have incentives to invest aggressively in R&D so as to exclude rivals and preserve their existing market power (Gilbert and Newbery 1982).

Despite its limitations, the simple model provides some important observations about merger effects. Rivalry generally promotes innovation, but with diminishing returns, if there are no spillovers or existing profits that are at risk from innovation. Rivalry has only small effects on innovation if R&D projects succeed with very high or very low probability, and the effect can be negative in the former case. A merger to monopoly typically has dramatic adverse impacts on the probability of discovery and consumer welfare if there are no technological spillovers that a monopolist can internalize.

Mergers can reduce innovation incentives by increasing the profits that are at risk from a discovery. The profits at risk do not have to come from products that are substitutes. But mergers can also increase innovation incentives by making it easier to appropriate value from a discovery by internalizing spillovers or by increasing the incremental profit from a discovery in the presence of competition from existing products.

Absent spillovers, mergers typically harm consumers by reducing future price competition, even if they increase the probability of a discovery. However, mergers that increase the probability of discovery can increase total expected consumer surplus if spillovers benefit firms and consumers in markets other than the market in which the innovation occurs.

Merger enforcement is the most commonly used tool in the antitrust toolkit. The simple model shows that the effects of mergers on innovation and consumer welfare are complex and warrant further study.

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Appendix: Proofs of Propositions

Proposition 1 *Part (i): If the only payoff occurs if a firm is the sole successful inventor, then from Eq. (5),*

$$-\ln(q)q^n q^{n(R-1)}\pi(1) = k$$

for all n and R . Hence the equilibrium total investment nR and the probability of discovery $Y(R)$ are independent of the number of firms R . This proves the first part of the theorem.

Part (ii): Let n be each firm's profit-maximizing number of R&D projects in an industry with R firms and n' be the profit-maximizing number of R&D projects with $R - 1$ firms. If we assume that $\pi(j) = 0$ for $R > \bar{R}$, Eq. (5) requires that

$$\sum_{j=0}^{\bar{R}} \frac{(R-1)!}{j!(R-1-j)!} q^{n(R-j)} (1-q^n)^j \pi(j+1) = \sum_{j=0}^{\bar{R}} \frac{(R-2)!}{j!(R-2-j)!} q^{n'(R-1-j)} (1-q^{n'})^j \pi(j+1). \quad (12)$$

Suppose $n'(R-1) \rightarrow nR$ and therefore $n' \rightarrow n$ as $R \rightarrow \infty$. Then in the limit equation (12) becomes

$$\sum_{j=0}^{\bar{R}} \left(\frac{j}{R-1-j} \right) \left[\frac{(R-2)!}{j!(R-2-j)!} q^{n(R-j)} (1-q^n)^j \pi(j+1) \right]. \quad (13)$$

This must be zero in the limit as $R \rightarrow \infty$ because the first term in brackets approaches zero and the sum of the second term in brackets is finite. Therefore $n'(R-1) \rightarrow nR$ in the limit as $R \rightarrow \infty$.

Proposition 2 Consider a reduction in rivalry from $R=2$ to $R=1$. If $\pi(j) = 0$ for $j \geq 2$ and $q \in (0, 1)$, Eq. (4) implies

$$q^{n'} \pi(1) = q^{2n} \pi(1) + q^n \pi(2).$$

If $\pi(1) > \pi(2) > 0$, this can be satisfied only if $n' < 2n$. Therefore, a merger to monopoly decreases the probability of discovery.

Proposition 3 Without loss of generality, let $\pi(1) = 1$ and $\pi(2) = \alpha$. If $\pi(j) = 0$ for $j > 2$, Eq. (5) requires

$$q^{nR} [1 + (R-1)\alpha h(n)] = z, \quad (14)$$

where

$$h(n) = \frac{1 - q^n}{q^n},$$

$$z = -\frac{k}{\ln(q)},$$

and n is the equilibrium number of projects chosen by each firm in an industry with R rivals. Furthermore,

$$q^{nR} [1 + (R-1)\alpha h(n)] = q^{n'(R+1)} [1 + R\alpha h(n')], \quad (15)$$

where n' is the equilibrium number of projects chosen by each firm in an industry with $R+1$ rivals. In the limit as $q \rightarrow 0$, Eq (14) implies

$$q^n = \left(\frac{z/\alpha}{R-1} \right)^{\frac{1}{(R-1)}}, \quad (16)$$

and

$$q^{n'} = \left(\frac{z/\alpha}{R} \right)^{\frac{1}{R}}. \quad (17)$$

Equation (15) with $\gamma \equiv n'(R+1) - nR$ is

$$1 + \alpha(R-1)h(n) = q^\gamma [1 + \alpha Rh(n')].$$

A sufficient condition for $\gamma < 0$ (which corresponds to $Y(R+1) < Y(R)$) is

$$(R-1)h(n) > Rh(n').$$

Substituting Eqs. (16) and (17), this condition is

$$\left(\frac{z}{\alpha R} \right)^{\frac{1}{R(R-1)}} - \frac{1}{R} \left(\frac{z}{\alpha R} \right)^{\frac{1}{(R-1)}} < \left(\frac{R-1}{R} \right)^{\frac{R}{R-1}}. \quad (18)$$

Inequality (18) is satisfied if z is sufficiently small, which corresponds to $q < \tilde{q}(R)$ with $\tilde{q}(R) > 0$. In that case, γ must be negative, which implies that $n'(R+1) < nR$ and $Y(R+1) < Y(R)$.

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