Monopsony Power and Upstream Innovation*

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Abstract

How does a monopsonist incentivize its supplier to innovate? By decreasing the short-run profit of the supplier, the monopsonist can increase the supplier's incentive to invest in R&D by lessening the supplier's Arrow's replacement effect. The monopsonist engages in this practice despite a distortion in its trade volume with the supplier that causes inefficiency. We discuss implications for the boundaries of the firm.

Keywords: Monopsony, innovation, vertical relationships, boundaries of the firm

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1 Introduction

Firms in innovative industries rely on global supply chains to create new products. For example, Boeing reports having contracts with more than 20,000 diverse suppliers and partners.[1] A natural question to ask is then: How does a firm incentivize R&D that takes place outside of its boundaries?

News reports suggest that companies like Tesla, Apple, Boeing, and other firms in innovative industries "squeeze" their suppliers when needing to improve their products. For example, Apple suppliers reported that Apple cut component prices and order volumes in 2016, promising that terms would improve after new-device launches.[2] Ford cut component prices by 3.5 percent in 2003 and requested suppliers to develop design cost savings of 20%.[3] "Squeezing"—which we define as cuts in input prices and order volumes—happens even though suppliers play a crucial role in developing innovations for the supply chain.

Is the "squeezing" consistent with downstream firms seeking to incentivize upstream innovation? A firm's incentive to innovate crucially depends on Arrow's replacement effect (Arrow, 1962), which measures the difference between the profit flow of the new product (i.e., the innovation) and that of the existing product. When this profit difference is small, the incentives to invest are small, as the firm has little to gain by replacing its existing product. The opposite is true when the profit difference is large. A strategic downstream firm with monoposony power (*monopsonist*, henceforth) can therefore squeeze its supplier to boost its supplier's R&D incentives, as squeezing decreases the supplier's profit, lessening the supplier's Arrow's replacement effect. From the perspective of the monopsonist, squeezing is productive in incentivizing upstream innovation, but we show that it is costly in terms of efficiency, as it forces a distortion in the trade volume along the supply chain.

We formally show the existence of the squeezing incentive in the context of a model of a vertical supply chain with upstream innovation. The model features a downstream monopsonist procuring inputs from a supplier. The supplier has the ability to invest in R&D to develop an innovation that enhances the value of the supply chain. In the baseline model, we assume that the monopsonist uses a linear contract in its dealings with the supplier and must use the linear contract to incentivize production and R&D. We make this choice inspired by our motivating examples and growing evidence on the use of linear contracts along vertical supply chains.[4] We show that our results extend to the case of non-linear contracts in an

[1]https://www.boeing.com/global/

[2]https://www.wsj.com/articles/apple-squeezes-parts-suppliers-to-protect-margins-1472713073

[3]https://www.wsj.com/articles/SB10691146306292100

[4]See, for example, Luco and Marshall (2020); Bajo-Buenestado and Borrella-Mas (2020); Marshall (2020)).

extension.

In the model, in every period of the game, the monopsonist sets an input price, and the supplier responds by choosing how many units of the input to supply and how much to invest in R&D (i.e., a Poisson arrival rate that governs the speed at which the innovation is invented). The supplier faces convex costs of production, which imply that its supply curve is increasing in the input price.[5] The monopsonist faces a revenue function that is increasing in the input quantity (i.e., more inputs enable more downstream production and revenue), which implies that squeezing is costly for the monopsonist, as it implies a distortion in input volumes (and thus revenue).

How does the monopsonist set its price? The monopsonist chooses its input price by setting marginal revenue equal to marginal cost, where marginal cost has three components. The first two relate to upstream production. When the supply curve is increasing in input price, demanding an extra unit of the input implies increasing the input price (first effect). Since the contract is linear, this input price increase applies to all inframarginal units as well (second effect). The third effect is that demanding an extra unit of the input (or increasing the input price), increases the profit flow of the supplier, magnifying its Arrow's replacement effect and thus inducing less upstream R&D. Purchasing the extra unit of the input is thus costly for the monopsonist because the monopsonist wishes to obtain the innovation as soon as possible, and less R&D will delay its arrival. This third effect creates the incentive to squeeze the supplier so long the supplier is working on the R&D project.

The squeezing effect magnifies the inefficiency caused by the downstream firm's monopsony power: to sustain the squeezing, trade between the monopsonist and the supplier decreases, which forces the monopsonist to sell fewer units of the downstream product and earn less revenue. This efficiency loss, caused by the squeezing effect, motivates us to ask: When will the squeezing effect cause firms to reshape their boundaries? We consider two possibilities: i) the supplier and downstream firm vertically integrate, ii) the supplier divests its research capabilities and a third-party firm takes up that activity. Starting from situations where firms would not want to change their boundaries in the absence of squeezing, we find that firms only reshape their boundaries when the magnitude of the innovation is sufficiently large, which is when the squeezing effect is exacerbated. Combined, these results can explain why firms in innovative industries are squeezing their suppliers and why we do not observe them revising their boundaries to avoid the efficiency loss of squeezing.

Our work relates to the literature studying how firms seek to affect the behavior of rival firms

[5]The supply curve is defined as the number of units that the supplier is willing to supply at input price w.

by strategically manipulating product-market profits. Gallini (1984) shows that incumbents may have an incentive to licence their innovations to entrants to boost entrants' profits and decrease their incentives to invest in R&D. Relatedly, Marshall and Parra (2021) show that firms have incentive to increase their prices to soften price competition and decrease the R&D incentives of rival firms. Byford and Gans (2014, 2019) show that in a natural oligopoly, it can be profitable for a firm to raise its price when this avoids the exit of a weak rival, where the goal is to prevent the weak rival from being replaced by a stronger competitor.

Our work also relates to the literature on the theory of the firm (Coase, 1937), and in particular, to the work on the impact of ownership (or vertical structure) on investments in relationship-specific assets (Williamson, 1975, 1979; Joskow, 1985; Grossman and Hart, 1986; Joskow, 1988). Lastly, we contribute to the literature on innovation incentives (Schumpeter, 1942; Arrow, 1962). Our model of R&D is in part based on work by Loury (1979), Lee and Wilde (1980), and Reinganum (1982) and our results speak to the relationship between vertical structure and innovation (Armour and Teece, 1980; Acemoglu *et al.*, 2003; Brocas, 2003; Chen and Sappington, 2010; Liu, 2016; Yang, 2020).

Finally, this article contributes to a growing literature on how market power affects innovation outcomes. This relation has been studied in the context of (killer) acquisitions (Cunningham *et al.*, 2021; Letina *et al.*, 2021) and horizontal mergers (Letina, 2016; Federico *et al.*, 2017, 2018; Denicolò and Polo, 2018; Hollenbeck, 2020; Motta and Tarantino, 2021). We contribute to this literature by studying how vertical market power and how changes in the vertical boundaries of the firm affect innovation outcomes.

2 A Model of Monopsony and Upstream Innovation

Set up Consider a monopsonist acquiring inputs from a supplier using a linear contract. The monopsonist chooses the input price w. The supplier, which takes the price w as given, chooses how much input q to sell. The supplier's cost of producing q units is given by the cost function $c(q)$, which is convex and twice differentiable, satisfying $c'(0) = 0$, $c'(q) > 0$ and $c''(q) > 0$ for all $q > 0$. The monopsonist derives revenue $R(q)$ when purchasing q units of the input. The revenue function is increasing, weakly concave and twice differentiable, satisfying $R(0) = 0$, $R'(q) > 0$ and $R''(q) \leq 0$ for all $q > 0$.

The supplier has an R&D investment opportunity, which is uncertain and would cause an increase in the monopsonist's revenue. Let $i \in \{0, 1\}$ be an index denoting whether an innovation has been achieved. Except where noted, we assume that state i is verifiable by third parties, making innovation-contingent contracts enforceable in court. Let $R_i(q)$ denote the monopsonist's revenue under technology i. We assume that, for all q $R_1'(q) > R_0'(q)$, which implies that $R_1(q) > R_0(q)$. That is, the innovation increases the revenue achieved with a given level of inputs. This formulation accommodates the cases of cost-saving and quality innovations.

Time is continuous and payoffs are discounted at a rate $r > 0$. Before the innovation has been invented ($i = 0$), the supplier makes simultaneous production and R&D investment choices at every instant of time given the state variable w, which is the input price set by the monopsonist. The supplier makes its R&D investment choice by choosing a Poisson innovation rate x at a convex R&D cost of $\kappa(x)$, which satisfies $\kappa(0) = 0$, $\kappa'(x) > 0$ and $\kappa''(x) > 0$ for all $x > 0$. The convex costs (of R&D and production) and concave revenue assumptions guarantee that second-order conditions hold throughout the article.

Equilibrium without R&D At every instant in time, given the input price w set by the monopsonist, the supplier chooses the quantity q that maximizes its profit. Because production decisions are time independent, the dynamic problem reduces to a static monopsony pricing problem. That is, the supplier solves

$$\pi_s(w) = \max_q \{w \cdot q - c(q)\}. \tag{1}$$

The optimal input quantity chosen by the supplier is given by the solution to the equation

$$w = c'(q). \tag{2}$$

Using the envelope theorem, we can verify that the supplier's profit is increasing in w and equal to $\pi_s'(w) = q(w)$. Equation (2) also gives an implicit expression for the supplier's supply curve, $q(w)$, which is increasing in w: $q'(w) = 1/c''(q(w)) > 0$.

Knowing the supplier's reponse to w, $q(w)$, under technology i, the monopsonist chooses the optimal linear contract w_i that solves

$$\pi_i^m \equiv \max_{w_i} \{R_i(q(w_i)) - w_i \cdot q(w_i)\}. \tag{3}$$

The optimal pricing condition is given by input price that equates the monopsonist's marginal revenue to its marginal costs, that is

$$R_i'(q(w_i)) = w_i \left(1 + \frac{1}{e^s(w_i)}\right), \tag{4}$$

The monopsonist's marginal cost consists of the average input price w_i plus the extra cost

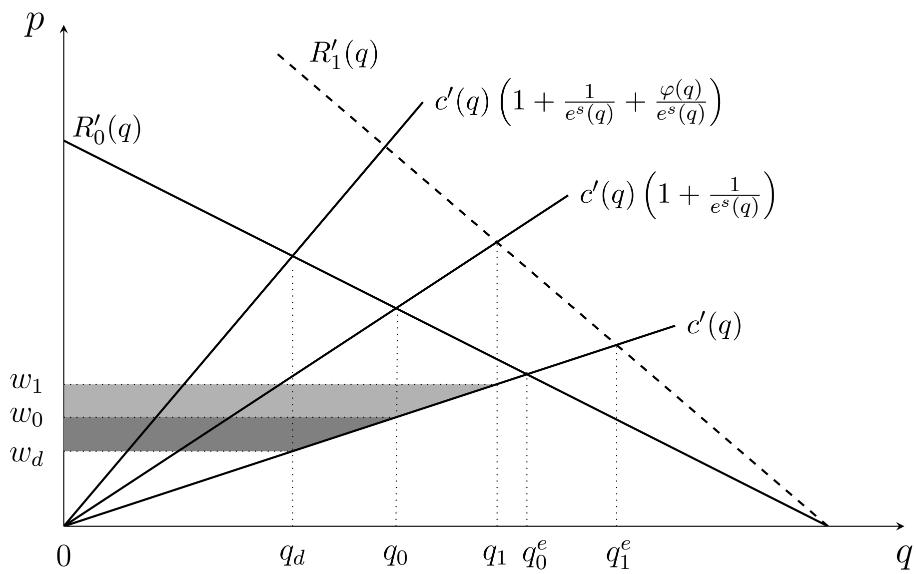

Figure 1: Innovation incentives. Depiction of the marginal revenue curves (before and after the innovation) and the marginal cost curves (of production, for the myopic monopsonist, and the dynamic monopsonist.) The shaded area illustrates the suppliers' incentives to innovate, i.e., the incremental profit $\pi_s(w_1) - \pi_s(w_d)$ associated with the innovation. The dark-shaded area represents the extra innovation incentives induced by the monopsonist squeezing the supplier.

that the monopsonist must pay for all inframarginal units when demanding an additional unit—recall that the supply curve is upward-sloping. The latter term is given by $w_i/e^s(w_i)$, which depends on the elasticity of the supply curve at w_i (i.e., $e^s(w) \equiv \partial q(w)/\partial w \cdot w/q(w)$). Figure 1 plots the left- and right-hand sides of equation (4), making use of the supplier's optimality condition $w = c'(q)$ in equation (2). It also shows the optimal input price w_i and quantity q_i. At the solution w_i, the monopsonist and the supplier earn the values $V_i^m = \pi_i^m/r$ and $V_i^s = \pi_s(w_i)/r$, respectively.

Efficient benchmark The efficient outcome is given by the output that equates marginal revenue to marginal cost of production, i.e., $R_i'(q_i^e) = c'(q_i^e)$. Later in the article, this will correspond to the output of a vertically integrated firm. Figure 1 illustrates the efficient output under technology i, q_i^e.

Upstream Innovation We now analyze the supplier's incentives to invest in the R&D project and how the monopsonist can manipulate these incentives with the linear contract that governs the vertical supply chain. At every instant in time, the supplier maximizes its value by solving

$$rV_0^s(w) = \max_x\{\pi_s(w) - \kappa(x) + x(V_1^s - V_0^s(w))\}, \tag{5}$$

where we leverage that the optimal production and R&D decisions are separable from the supplier's perspective and $\pi_s(w)$ is the supplier profit function defined in equation (1). The supplier's value given input price w, $V_0^s(w)$, is the discounted sum of its profit flow $\pi_s(w)$, net of R&D costs, plus the increase in value from an innovation $V_1^s - V_0^s(w)$, which is obtained at rate x.

The solution to this problem, $x^*(w)$, solves the equation

$$\kappa'(x) = V_1^s - V_0^s(w). \tag{6}$$

The supplier invests according to the incremental value it obtains from the innovation, which is the difference between the supplier's value with and without an innovation: $V_1^s - V_0^s(w)$. This value difference induces a *replacement effect* (Arrow, 1962) in that the supplier is less willing to invest in R&D when the supplier has less to gain from the innovation (i.e., when the pre-innovation value $V_0^s(w)$ is high relative to V_1^s).

Understanding the replacement effect at play, the monopsonist can influence the supplier's R&D investment via its choice of input price w. Specifically, the monopsonist can change w to affect the supplier's pre-innovation value, $V_0^s(w)$, and manipulate the replacement effect faced by the supplier. Using implicit differentiation and the envelope theorem, we can compute the impact of the input price w on the supplier's R&D investment:

$$\frac{\partial x^*(w)}{\partial w} = -\frac{1}{\kappa''(x^*(w))}\frac{\partial V_0^s(w)}{\partial w} = \frac{-\pi_s'(w)}{\kappa''(x^*(w))(r + x^*(w))} < 0.$$

That is, an increase in the input price leads to a lower R&D investment. Why? An increase in the input price raises the supplier's pre-innovation profit flow by $\pi_s'(w)$, which benefits the supplier until the innovation arrives, causing a value increase of $\pi_s'(w)/(r + x^*(w))$. This increase in $V_0^s(w)$ decreases the incremental rent of an innovation in equation (6), which results in a decrease in the incentives to innovate.[6]

Consider now the monopsonist's problem of choosing the optimal w for the pre-innovation phase of the game. At every instant of time, it solves

$$rV_0^m = \max_w \{R_0(q(w)) - w \cdot q(w) + x^*(w)(V_1^m - V_0^m)\},$$

where the monopsonist's value at instant t equals its revenue flow, minus the total cost of its inputs, plus the incremental value of an innovation $V_1^m - V_0^m$, which arrives at a rate $x^*(w)$.

[6]The factor $1/\kappa''(x^*)$ simply translates the change in incremental rents to changes in the arrival rate via the R&D cost function.

Using the first-order condition and $\pi_s'(w) = q(w)$, we obtain

$$R_0'(q(w)) = w\left(1 + \frac{1}{e^s(w)} + \frac{\varphi(w)}{e^s(w)}\right), \quad \text{where} \quad \varphi(w) = \frac{V_1^m - V_0^m}{(r + x^*(w))\kappa''(x^*(w))} > 0. \tag{7}$$

Equation (7) captures the monopsonist's incentives to price in the presence of an innovation project. As before, the monopsonist's optimal input price is the one where marginal revenue equals marginal cost. The marginal cost consists of three terms. The first two correspond to the traditional marginal costs of the monopsonist, as discussed in equation (4). The third term captures that the gain in future value $V_1^m - V_0^m$ is delayed when increasing w as a result of a decrease in the rate of innovation (i.e., $\partial x^*/\partial w < 0$). That is, a higher input price increases the revenue of the monopolist but it also increases the per-unit price paid for the input and decreases the supplier's incentives to invest in R&D. We call the optimal dynamic pricing decision w_d.

Figure 1 plots both sides of equation (7) and illustrates the solution w_d. Compared with the monopsonist's marginal cost in the absence of innovation, the marginal cost under the possibility of an upstream innovation is larger by a factor of $w\varphi(w)/e^s(w) > 0$. This term captures how an increase in w delays the innovation benefits accrued by the monopsonist as a result of decreased R&D incentives. This delay shifts the marginal cost curve upwards, inducing the monopsonist to always set an input price that is lower than when innovation is not a possibility. That is, the possibility of an upstream innovation induces monopsonist to squeeze the supplier with a lower w, decreasing the supplier's pre-innovation value $V_0^s(w)$ and boosting its R&D incentives.[7]

Theorem 1. *The optimal input price set by a monopsonist in the possibility of an upstream innovation is lower than the input price set by a monopsonist in the absence of innovation. That is, $w_d < w_0$.*

3 Upstream Innovation and the Firms' Boundaries

The vertical supply chain in our baseline model features three activities: downstream production, upstream production, and upstream innovation. Our motivating examples feature a downstream firm performing the first and an upstream firm performing the latter two. Under this vertical structure, the presence of the innovation project creates incentive to squeeze the supplier, which while productive in incentivizing innovation, is costly in terms of efficiency:

[7]The figure also shows that $w_1 > w_0$ because the innovation increases the marginal rent that the monopsonist derives from the input while keeping the marginal cost curve fixed.

as Figure 1 shows, squeezing the supplier pushes the output choice q_d further away from the efficient quantity q_0^e. This raises the question of whether this vertical structure is stable in the presence of the innovation project. Or in other words, whether the impact of squeezing on efficiency is motive to redraw the boundaries of the firms along the vertical supply chain.

We consider two deviations from the baseline vertical structure and ask whether firms have an incentive to redraw their boundaries in presence of supplier squeezing. The first is vertical integration between the supplier and the downstream firm (i.e., all activities performed by a single firm) and the second is the case when all activities are performed by separate firms (i.e., the supplier divests its R&D capabilities).

In what follows, we make three functional assumptions to obtain analytical results. We assume that: (i) $R_i(q) = \alpha^i \cdot q$, where $\alpha > 1$ represents the magnitude of the innovation; (ii) $c(q) = q^2/2$, and; (iii) $\kappa(x) = x^2/2$. Assumption (i) is somewhat innocuous: as equation (7) shows, the squeezing incentive is driven by the the costs side. Assumptions (ii) and (iii) impose a particular structure to the supply functions of the input and R&D, which feed into the monopsonist's marginal costs. However, numerical analysis suggests that the findings below are robust.

In the analysis below we present the key equations to understand the model. Self-contained proofs of the propositions are in the Appendix and a step-by-step derivation of the models' analytical solutions are presented in the Online-Appendix.

Baseline Solution Using the first-order condition in equation (6) and assumption (iii), we obtain $x^*(w) = V_1^s - V_0^s(w)$. Plugging this expression for $x^*(w)$ into equation (5), we can solve for the supplier's pre-innovation value $V_0^s(w)$ and the pace of innovation as a function of the input price w:

$$x^*(w) = \sqrt{r^2 + 2\Delta_s(w)} - r, \tag{8}$$

where $\Delta_s(w) \equiv \pi^s(w_1) - \pi^s(w)$ is the incremental profit flow earned by the supplier when achieving the innovation.[8] Following similar steps, we can solve for the monopsonist's incremental value, $V_1^m - V_0^m$. Replacing the incremental value into the monopsonist's optimal pricing condition in equation (7) we obtain

$$1 = 2w + \frac{w(\alpha^2/4 - (w - w^2))}{(\alpha^2/4 + r^2 - w^2)}. \tag{9}$$

[8] In Marshall and Parra (2019), we show that the shape of the incremental profit flow with respect to the number of competitors determines the relationship between innovation and competition.

This third-degree polynomial has three analytic solutions, but only one of them imply positive profits, quantities, and prices. We call this solution w_d, which is function of the only two parameters of the model: α and r.

Lemma 1. *The optimal dynamic input price set by the monopsonist* $w_d \in (1/3, 1/2]$ *is decreasing in* α *and increasing in* r*.*

The dynamic input price w_d decreases in the magnitude of the innovation. As the innovation becomes more valuable, there are more incentives to squeeze the supplier, inducing a faster pace of innovation. Similarly, as the discount rate increases, the future innovations are worth less, creating less incentive to squeeze the supplier. The input price converges to $w_0 = 1/2$ when the value of the innovation goes to zero ($\alpha = 1$) and has a lower bound of $1/3$, where the incentive to squeeze the supplier is at its highest point.

Full Vertical Integration We first consider whether the supplier and monopsonist would want to vertically integrate (i.e., all activities conducted by a single firm).

At every instant of time, the vertically-integrated firm chooses its input quantity and R&D investment:

$$rV_0^{vi} = \max_{q,x}\{R_0(q) - c(q) - \kappa(x) + x(V_1^{vi} - V_0^{vi}),\} \tag{10}$$

where the flow value of the integrated firm before the innovation arrives equals the full surplus generated by the supply chain plus the incremental value of an innovation, arriving at rate x, net of R&D costs. The firm chooses to produce the efficient input quantity, q_i^e. We define $\pi_i^{vi} \equiv R_i(q_i^e) - c(q_i^e)$ and $rV_1^{vi} = \pi_1^{vi}$. The first-order condition with respect to the R&D investment is $x_{vi} = V_1^{vi} - V_0^{vi}$. Plugging this expression for x_{vi} into equation (10), we can solve for the value of the vertically-integrated firm as well as the equilibrium R&D investment:

$$x_{vi} = \sqrt{r^2 + 2\Delta_{vi}} - r, \tag{11}$$

where $\Delta_{vi} = \pi_1^{vi} - \pi_0^{vi}$ is the incremental profit flow that the supplier earns when achieving the innovation.

How do market outcomes compare with and without vertical integration? Comparing the pace of innovation under both vertical structures (see equations (8) and (11)) amounts to comparing the values of the incremental profit flows (i.e., Δ_{vi} and $\Delta_s(w_d)$). It turns out that when the magnitude of the innovation and discounting are both small, the (vertically-independent) supplier's incremental profit flow can be larger than that of the vertically-integrated firm. This situation is illustrated in Figure 2. The lightly-shaded area represents the incremental profit flow of the vertically integrated firm, whereas the dark-shaded area represents the in-

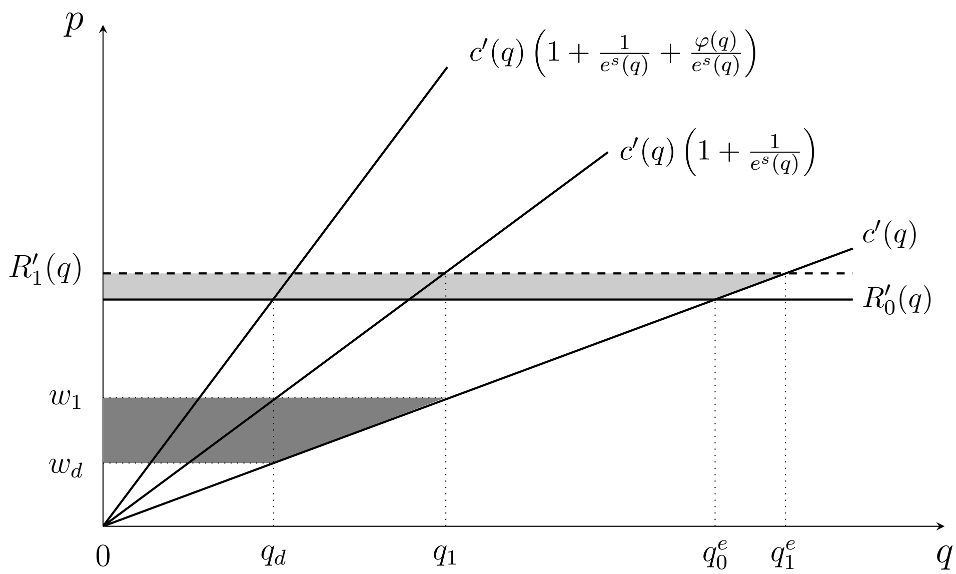

Figure 2: Innovation incentives and boundaries pf the firm. Depiction of the marginal revenue curves (before and after the innovation) and the marginal cost curves (of production, for the myopic monopsonist, and the dynamic monopsonist.) The light-shaded area illustrates the innovation incentives of a vertically integrated firm, $\Delta_{vi} = \pi_1^{vi} - \pi_0^{vi}$. The dark-shaded area represents the innovation incentives of a squeezed supplier, $\Delta_s(w_d) = \pi_s(w_1) - \pi_s(w_d)$.

cremental profit flow of the vertically-independent supplier. As α decreases towards one (no innovation), the lightly-shaded decreases proportionally to α. In contrast, the decrease in the size of the dark-shaded area depends on the discount rate r. The smaller the discount rate, the dynamic effects become more relevant, slowing the rate at which the vertically-independent supplier's incremental profit flow decreases. When α is sufficiently close to one, this causes the supplier to perform faster innovation than the vertically-integrated firm.

Proposition 1. *For a small innovation (i.e., an α close to 1), there exists a discount rate r such that the vertically-independent supplier makes a greater R&D investment than the fully-integrated firm; i.e., $x^*(w_d) > x^{vi}$.*

Despite the potential for a faster speed of innovation in the absence of vertical integration, the supplier and monopsonist can achieve a larger joint value by vertically integrating as long as the bureaucracy costs of performing and organizing all activities within a single firm are sufficiently low (Coase, 1937), where we model the bureaucracy costs of vertical integration as a flow cost K that is paid at every instant of time in which the firms are integrated. The potential for a greater joint value stems from the fact that the squeezing incentive causes inefficiencies in production and R&D, which imply a loss in joint value.

We consider bureaucracy costs that are sufficiently high that the supplier and monopsonist would choose to remain independent in the absence of an innovation project (or when the squeezing incentive is not present). Formally, we consider bureaucracy costs that are larger than $\hat{K}$, which is defined as $\hat{K} = \pi_0^{vi} - (\pi_0^m + \pi_s(w_0))$. In such high-bureaucracy costs situations, when does the squeezing incentive motivate the monopsonist and supplier to vertically integrate? The following proposition shows that the firms do not have an incentive to integrate unless the magnitude of the innovation α is sufficiently large. That is, if in the absence of the squeezing effect the firms would not want to integrate, the inefficiencies caused by the squeezing effect do not justify vertical integration unless the value of the innovation is sufficiently high. This suggests that vertical independence of the supplier and monopsonist is a stable vertical arrangement as long as the size of the innovation is small.

Proposition 2. *For every cost $K > \hat{K}$, there exist thresholds $\underline{\alpha}$ and $\bar{\alpha}$, where $\underline{\alpha} \leq \bar{\alpha}$, such that the firms choose not to vertically integrate when $\alpha < \underline{\alpha}$ and to vertically integrate when $\alpha > \bar{\alpha}$.*

Three Separate Firms We next consider whether the supplier would want to divest its research capabilities when the squeezing effect is at play. In this case, all activities would be conducted by separate firms, where the R&D is conducted by a firm we call "the lab". As we will show, the supplier benefits from divesting its research capabilities because the monopsonist would no longer have the squeezing incentive. However, divesting its research capabilities implies that the supplier must share its rents with the lab and pay transaction costs (e.g., monitoring costs) from having to deal with a third-party firm (Coase, 1937). We model these transaction costs as a flow cost F, which are paid as long as the R&D is conducted outside the boundaries of the supplier.

For simplicity, we consider a lump-sump contract between the supplier and the lab. That is, after an innovation is achieved, the supplier pays a lump-sum transfer T to the research lab. In line with our analysis of the baseline model, we assume that there is a "contracting stage" followed by a production/investment stage. That is, the monopsonist and supplier make simultaneous announcements of w and T, and the supplier and lab then make production and R&D investment decisions given these values.

Because the monopsonist cannot directly influence the lump-sum transfer T set by the supplier, the monopsonist chooses its input price according to equation (4). That is, the squeezing effect vanishes when the supplier divests its research capabilities.

The research lab must choose how much to invest in R&D given the transfer T. That is, the research lab solves

$$rL = \max_x \{-\kappa(x) + x(T - L)\},$$

where L is the value of the research lab before the innovation. The flow value of being an independent lab, rL, corresponds to the flow cost of R&D plus the incremental rent obtained from an innovation, $T - L$, which arrives at a rate $x_\ell(T)$. Under assumption (iii), the first-order condition with respect to the R&D investment becomes $x_\ell = T - L$. Using this expression we can then solve for the lab's value and its R&D investment as a function of T:

$$x_\ell(T) = \sqrt{r^2 + 2rT} - r. \tag{12}$$

Given the lab's investment decision, we solve for the optimal transfer from the supplier's perspective. Let S be the supplier's pre-innovation value when it has divested its research capabilities. This value is given by

$$rS = \max_T \{\pi_s(w_0) + x_\ell(T)(V_1^s - S - T)\} \tag{13}$$

That is, the flow value of being a supplier without research capabilities, rS, equals the pre-innovation profit flow plus the incremental rent from an innovation net of the lump-sum transfer to the lab, $V_1^s - S - T$, which arrives at rate $x_\ell(T)$. Using the first-order condition of (13), we can analytically solve for the optimal lump-sum T as a function of r and the supplier's incremental value of an innovation $V_1^s - S$. With the lump-sum's solution, we can solve for the supplier's value S (see the Appendix for the solutions).

How does the vertical structure impact R&D outcomes? In the absence of squeezing, the incremental value of an innovation for the supplier without research capabilities is lower than that for the supplier with research capabilities. This is a consequence of the squeezing incentive: when the supplier is performing the R&D, the monopsonist manipulates w to magnify the supplier's incremental value of an innovation to boost R&D incentives. In addition, these lower incremental rents need to be shared with the lab in order to induce innovation. As a result, the lab innovates at a lower pace than a supplier with research capabilities.

Proposition 3. *For every innovation magnitude $\alpha > 1$, the lab invests at a lower pace than the supplier with research capabilities.*

The supplier must then consider several effects when deciding whether to divest its research capabilities. On the one hand, dealing with a third-party firm creates transaction costs F for the supplier. On the other hand, divesting increases productive efficiency along the supply chain, as the downstream firm can no longer squeeze the supplier. The following proposition shows that when the transaction costs are sufficiently high, research capabilities are never divested, as expected. The divestiture can only happen when the transaction costs are sufficiently low and the magnitude of the innovation is sufficiently high. That is, research capabilities are never divested for small innovations.

Proposition 4. *There exists a level of transaction costs $\overline{F}$ such that if $F > \overline{F}$ the supplier never divests its research capabilities. For every transaction cost $F \in (0, \overline{F})$, there exist thresholds $1 < \underline{\alpha} < \overline{\alpha}$ such that the research capabilities are divested if $\alpha \in (\underline{\alpha}, \overline{\alpha})$ and are not divested otherwise.*

These results combined show that despite the efficiency loss caused by the squeezing effect, the vertical structure in our baseline model is stable if the size of the innovation is sufficiently small. As a result, our theory can rationalize the squeezing that is observed in our motivating examples and why downstream firms choose to keep research capabilities outside its boundaries.

4 Extensions

In the baseline model, we make two modelling assumptions that we relax in this section. The first is that the monopsonist uses a linear contract in its dealing with the supplier; the second is that arrival of the innovation is verifiable by outside parties, making innovation-contingent contracts enforceable in court.

4.1 Non-linear Contracts

Although linear contracts are ubiquitous, these are inefficient and do not allow the monopsonist to exert its market power fully. We show that squeezing also arises in the context of efficient non-linear contracts. Here we maintain the assumption that the arrival of the innovation is verifiable by outside parties, making innovation-contingent contracts enforceable in court.

Consider a scenario in which the monopsonist asks the supplier to supply the efficient quantity (i.e., q_i^e) in exchange for a fixed transfer t. Without R&D, the monopsonist extracts all the surplus by paying $t_0 = c(q_0^e)$; i.e., the minimal transfer that ensures participation by the supplier. In the presence of R&D, the monopsonist offers and commits to the contract schedule (t_d, t_1), the pre- and post-innovation transfers. In this context, the post-innovation value equals $rV_1^s = t_1 - c(q_1^e)$, which is positive only if $t_1 > c(q_1^e)$.

The pre-innovation value of the supplier is then given by

$$rV_0^s(t_d) = \max_x \{t_d - c(q_0^e) + \kappa(x) + x(V_1^s - V_0^s(t_d))\}, \tag{14}$$

that is, the flow value of the supplier equals its profit flow (i.e., the transfer) plus the expected gain from an innovation net of R&D costs. Under assumption (iii), the first-order condition of the supplier's problem becomes $x_n = V_1^s - V_0^s(t_d)$, which we can replace back into equation (14) to solve for $V_0^s(t_d)$. Observe that the monopsonist can set a pre-innovation transfer that simultaneously minimizes the replacement effect and extracts all the pre-innovation rents of the supplier, i.e., $V_0^s = 0$. This transfer is given by $t_d = c(q_0^e) - (V_1^s)^2/2$ which is lower than t_0 when the supplier has an R&D project available. To see this, note that the monopsonist needs to give the supplier rents after the arrival of the innovation for there to be innovation incentives (i.e., $V_1^s > 0$). This allows the monopsonist to backload the supplier's compensation, and squeeze the supplier before the innovation's arrival to maximize R&D incentives.

Proposition 5. *The optimal transfer set by a monopsonist under an efficient non-linear contract is lower under the possibility of upstream innovation, i.e., $t_d < t_0$.*

4.2 Hold-up Problem

We next relax the assumption that the arrival of the innovation is verifiable by outside parties. In particular, we assume that the supplier and monopsonist can verify the arrival of the innovation, but third parties cannot, making innovation-contingent contract unenforceable in court. This implies that supplier might be subject to a hold-up problem (Williamson, 1975; Klein *et al.*, 1978; Williamson, 1979), which means that after the arrival of the innovation, the monopsonist may change the terms of the contract to expropriate the supplier's rent.

To study such incentives, we extend the model to allow for a sequence of innovations for the supplier to undertake.[9] In this context, we show conditions under which the monopsonist never chooses to deviate to extract the full surplus of any future innovation (i.e., "hold up" the supplier), as this would make innovation incentives vanish, stopping the innovation process.

Let $i \in \{0, 1, 2, \ldots\}$ be an index denoting the number of innovations that have occurred. For tractability, we modify the previous model by assuming that $R_i(q) = \alpha^i q$, $c_i(q) = \alpha^i q^2/2$, and $\kappa_i(x) = \alpha^i x^2/2$, where α is the size of each innovation. That is, both revenue and costs increase proportionally to the innovation magnitude.

In this context, after i innovations have occurred, the first-order condition of the supplier's production problem (i.e., equation 1) becomes $w_i = \alpha^i q$. Given input price w_i, the supplier

[9] Other articles modelling sequential innovations include Grossman and Helpman (1991); Aghion and Howitt (1992); Aghion *et al.* (2001); Hopenhayn *et al.* (2006); Segal and Whinston (2007); Parra (2019).

also solves

$$rV_i^s(w_i) = \max_{x_i}\{\pi_i^s(w_i) - \kappa(x_i) + x_i(V_{i+1}^s(w_{i+1}) - V_i^s(w_i))\},$$

where the flow value of a supplier after i innovations equals the supplier's profit flow plus the incremental rent of an innovation net of R&D costs. The first-order condition of this problem is $x_i(w_i) = (V_{i+1}^s(w_{i+1}) - V_0^s(w_i))/\alpha^i$, with $\partial x_i/\partial w_i = -w_i/((\alpha^i)^2(r + x_i)) < 0$.

Similarly, the monopsonist's problem consists of choosing an input price that solves

$$rV_i^m = \max_{w_i}\left\{w_i - \frac{w_i^2}{\alpha^i} + x_i(w_i)(V_{i+1}^m - V_i^m)\right\},$$

where we use that $\pi_i^m(w) = w_i - w_i^2/\alpha^i$. Using the expression for $\partial x_i/\partial w_i$, the first-order condition of this problem becomes

$$1 - \frac{w_i}{\alpha^i}\left(2 + \frac{V_{i+1}^m - V_i^m}{\alpha^i(r + x_i)}\right) = 0. \tag{15}$$

We solve the game by making two conjectures that are verified in equilibrium: i) that the sequence of optimal prices is such that the input price increases at rate α with every innovation (i.e., $w_i = \alpha^i w_d$), and ii) that the equilibrium of the game features values of the form $V_i^j = \alpha^i V_0^j$ for $j \in \{m, s\}$. Using these conjectures, we find that equation (15), for every i, collapses to finding the price w_d that solves

$$1 - w_d\left(2 + \underbrace{\frac{\alpha - 1}{r + x_{seq}}V_0^m}_{\text{squeezing effect}<0}\right) = 0,$$

where $x_{seq} = (\alpha - 1)V_0^s$ is the innovation rate, which is independent of the number of innovations i, and the firms' values are given by

$$V_0^s = \frac{1}{(\alpha-1)^2}\left(r - \sqrt{r^2 - 2(\alpha-1)\pi_s(w_d)}\right) \qquad \text{and} \qquad V_0^m = \frac{\pi_0^m}{r - x_{seq}(\alpha - 1)}. \tag{16}$$

As the first-order condition shows, the squeezing effect exerts a downward pressure on pricing incentives, causing w_d to be lower than the price set by a monopsonist ignoring innovation effects.[10]

Would the monopsonist want to deviate from its sequence of prices to extract the full surplus

[10] We note that this solution is only defined for $r > \alpha - 1$. For larger values of α, the payoff growth associated caused by the innovations is too high and the values of the supplier and monopsonist diverge to infinity.

generated by any future innovation? In this case, the monopsonist would earn the total surplus generated by the supply chain when production decisions are efficient (i.e., where q solves $R_i'(q) = c_i'(q)$) for every innovation. That is, $V_i^{dev} = \pi_i^{vi}/r = \alpha^i \pi_0^{vi}/r$. The following proposition shows that the monopsonist would not make such a deviation when the discount rate is sufficiently small (i.e., the benefits of future innovations are not heavily discounted) or when the innovation size is large (i.e., the benefits of future innovations are large). That is, in such cases, it is in the monopsonist's best interest to preserve innovation incentives.

Proposition 6. *For a sufficiently small interest rate r or a sufficiently high innovation magnitude α, hold up does not arise in equilibrium. That is, $V_i^m > V_i^{dev}$ for every i.*

5 Conclusions

A monopsonist can enhance a supplier's R&D incentives by strategically lowering the input price, decreasing the supplier's short-run profit (i.e., squeezing), and attenuating Arrow's replacement effect. The monopsonist achieves a higher pace of innovation by distorting its trade volume with the supplier despite an efficiency loss. While the efficiency loss caused by this practice may be grounds for vertical integration (or, more broady, a change in the boundaries of the firms), we show that vertical integration only occurs when the magnitude of the innovation is sufficiently large, which is when the efficiency loss of squeezing is most severe. These results combined can rationalize two facts in our motivating examples: i) downstream firms with a dominant position in innovative industries squeeze their suppliers, ii) the vertical structure (i.e., vertical independence between the downstream firm and the supplier) is stable despite the inefficiency caused by squeezing.

Appendix

Proof of Theorem 1 $R_1(q) > R_0(q)$ imply $\pi_0^m < R_1(q(w_0)) - w_0 \cdot q(w_0) < \pi_1^m$; which, in turn, implies that $V_1^m > V_0^m$. Consequently, $\varphi(w) > 0$ and the right-hand side of (7) is always larger than the right-hand side of (4), proving the result. □

Proof of Lemma 1 Re-write first-order condition (9) as $\Gamma(w_d, \alpha, r) = 0$, where

$$\Gamma(w, \alpha, r) = (1 - 2w)(\alpha^2/4 + r^2 - w^2) - w(\alpha^2/4 + w^2 - w).$$

When no innovation exists ($\alpha = 1$), the optimal dynamic price equals the static one, that is $w_d = w_0 = 1/2$. Implicitly differentiating w_d, we obtain

$$\frac{\partial w_d}{\partial \alpha} = -\frac{\alpha(3w_d - 1)}{4r^2 + 3\alpha^2/2 - 6w_d^2} \qquad \text{and} \qquad \frac{\partial w_d}{\partial r} = \frac{4r\alpha(1 - 2w_d)}{4r^2 + 3\alpha^2/2 - 6w_d^2}. \tag{17}$$

When $\alpha = 1$, $\partial w_d/\partial \alpha = -1/(8r^2)$, implying that the optimal price w_d decreases in α in a neighborhood of $\alpha = 1$. Using the implicit derivative, we can see that this decrease implies that w_d is always decreasing in α and has an asymptote at $w_d = 1/3$. These observations also imply $\partial w_d/\partial r > 0$. □

Proof of Proposition 1 We show that $\Delta^s(w_d) - \Delta^{vi} = (4 - 3\alpha^2 - 4w_d^2)/8 > 0$ for small α and r. When $\alpha = 1$, $w_d = 1/2$ and $\Delta^s(w_d) - \Delta^{vi} = 0$. Differentiating with respect to α when $\alpha = 1$, we obtain

$$\left.\frac{\partial(\Delta^s(w_d) - \Delta^{vi})}{\partial \alpha}\right|_{\alpha=1} = -\left.\frac{1}{4}\left(3\alpha + w_d\frac{\partial w_d}{\partial \alpha}\right)\right|_{\alpha=1} = \frac{1}{4}\left(\frac{1}{16r^2} - 3\right),$$

where we used (17) evaluated at $\alpha = 1$. The derivative is positive for small enough r. □

Proof of Proposition 2 The firms vertically integrate whenever $V^{vi} - V_0^m - V_0^s(w_d) > K/r$. When $\alpha = 1$, $V^{vi} - V_0^m - V_0^s(w_d) = \hat{K}/r$. Thus, firms only integrate if $K < \hat{K}$. When $\alpha \to \infty$, the values V^{vi}, V_0^m, and $V_0^s(w_d)$ become unboundedly large. Because $\lim_{\alpha\to\infty} V^{vi}/(V_0^m + V_0^s(w_d)) = 4/3$ the difference $V^{vi} - (V_0^m + V_0^s(w_d))$ diverges, and vertically integration can occur for any integration cost $K > \hat{K}$. Taken together, these results imply that, by the intermediate value theorem, there exist thresholds $\underline{\alpha}$ and $\overline{\alpha}$, such that for every $K > \hat{K}$ integration does not occur if $\alpha < \underline{\alpha}$ and does occur if $\alpha > \overline{\alpha}$.

Proof of Proposition 3 Define $\mathcal{V} = V_s^1 - S$, the supplier's incremental value of an innovation. From equations (8) and (12) we can see that $x_\ell < x_s(w_d)$ if and only if $rT < \Delta_s(w_d)$. Supplier's problem (13) implies that $x_\ell > 0$ only if $\mathcal{V} > T$, then

$$rT < r\mathcal{V} = \pi_s(w_1) - \pi_s(w_0) - x_\ell(\mathcal{V} - T) < \pi_s(w_1) - \pi_s(w_0) < \Delta_s(w_d)$$

for every $\alpha > 1$. The last inequality follows from $w_d < 1/2$, so that $\Delta_s(w_d) = (\alpha^2 - 4w_d^2)/8 < (\alpha^2 - 1)/8 = \pi_s(w_1) - \pi_s(w_0)$, proving the result. □

Proof of Proposition 4 Let $\mathcal{V} = V_s^1 - S = \alpha/8 - S$, the optimal transfer to the lab T is found by solving the first order condition of problem (13) and is given by

$$T^*(S, \alpha, r) = \left(3\mathcal{V} - 2r + \sqrt{2r(2r + 3\mathcal{V})}\right) \Big/ 9.$$

Using T^*, we define $G(S, \alpha, r) = \pi_s(q_0) + x_\ell(T^*)(\mathcal{V} - T^*) - rS$. The value S is implicitly defined by $G(S, \alpha, r) = 0$. When $\alpha = 1$, $S = \pi_s(q_0)/r = V_s(w_d)$, i.e., there is no gain from divesting. Using implicit differentiation, we can show that $\partial S/\partial \alpha > 0$, i.e., the value of being a divested supplier increases in α. Differentiating $V_s(w_d)$ with respect α, we obtain

$$\frac{\partial V_s(w_d)}{\partial \alpha} = \frac{\alpha \left(\left(\sqrt{4r^2 + \alpha^2 - 4w_d^2} - 2r \right) \left(2r^2 + 3(\frac{\alpha^2}{4} - w_d^2) \right) - 4w_d(3w_d - 1)r \right)}{\left(2r^2 + 3(\frac{\alpha^2}{4} - w_d^2) \right) \sqrt{4r^2 + \alpha^2 - 4w_d^2}}$$

Because $w_d \leq 1/2$ and $\partial w_d/\partial \alpha > 0$, the denominator is positive. When $\alpha = 1$, the numerator is negative but increases in α, becoming positive for sufficiently large α. That is, $V_s(w_d)$ is U-shaped with $S > V_s(w_d)$ for low values of α. $V_s(w_d)$ and S diverge to infinity when $\alpha \to \infty$. Because $\lim_{\alpha \to \infty} V_s(w_d)/S = 1$, the difference $S - V_s(w_d)$ is also U-shaped, becoming arbitrarily small when α is large. Let $\overline{F}/r = S(\alpha^*) - V_s(w_d(\alpha^*))$ where α^* solves $\partial S(\alpha^*)/\partial \alpha = \partial V_s(w_d(\alpha^*))/\partial \alpha$; i.e., the α for which the difference in values is maximal. Then, for every $F < \overline{F}$, there exists $\underline{\alpha}$ and $\overline{\alpha}$ such that integration only occurs if $\alpha \in (\underline{\alpha}, \overline{\alpha})$. $\square$

Proof of Proposition 5 We show that $t_1^* > c(q_1^e)$. Replacing the supplier's optimal R&D investment, $x_n = V_1^s - V_0^s$, into its value function, we can solve for V_0^s. Using $rV_1^s = t_1 - c(q_1^e)$, we find $x_n = \sqrt{r^2 + 2(t_1 - c(q_1^e) - t_d + c(q_0^e))} - r$.

The monopsonist then solves $rV_0^m = \max_{t_d, t_1}\{R_0(q(w)) - t_d + x_n(V_1^m - V_0^m)\}$. Using x_n and $rV_1^m = R_1(q(w)) - t_1$, the problem becomes $rV_0^m =$

$$\max_{t_d, t_1} \left\{ R_0(q(w)) - t_d + \left(\sqrt{r^2 + 2(t_1 - c(q_1^e) - t_d + c(q_0^e))} - r \right) \left(\frac{R_1(q(w)) - t_1}{r} - V_0^m \right) \right\}$$

subject to supplier participation constraint $V_i^s \geq 0$. Because $\partial V_0^m/\partial t_d < 0$, the monopsonist wants to make t_d as small as possible. Therefore, the participation constraint at $i = 0$ binds and $t_d = c(q_0^e) - (t_1 - c(q_1^e))^2/2r$. Replacing t_d into V_0^m, differentiating with respect to t_1, and evaluating the derivative at $t_1 = c(q_1^e)$ (i.e., the lower transfer satisfying the supplier participation constraint), we obtain $\partial V_0^m/\partial t_1 = (R_1(q_1^e) - c(q_1^e) - rV_0^m)/r > (V_1^m - V_0^m) > 0$, proving $t_1^* > c(q_1^e)$. $\square$

Proof of Proposition 6 At any innovation i, maintaining the innovation process is preferred by the monopsonist over full surplus extraction if $V_i^{dev} < V_i^m$ or equivalently,

$$\pi_0^{vi} < r\pi_0^m \Big/ \sqrt{r^2 - 2(\alpha - 1)\pi_s(w_d)}\ .$$

This condition holds if r is sufficiently small or α is sufficiently large. $\square$

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Supplemental Material – Intended for Online Publication

Monopsony Power and Upstream Innovation

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A Analytic Solutions

For completeness, in this online appendix, we present the complete analytic solutions to the models in Sections 3 and 4. All relevant information to prove the results in the article is in the main appendix of the paper.

A.1 Boundaries of the Firms

Baseline model Under assumptions (i) and (ii) one can verify that: $w_i = q_i = \alpha^i/2$ (see equation 4), $\pi_s(w_i) = \alpha^{2\cdot i}/8$ (see equation 1), and $\pi_i^m = \alpha^{2\cdot i}/4$ (see equation 3). Using the first-order condition in equation (6) and assumption (iii), we obtain $x^*(w) = V_1^s - V_0^s(w)$. Plugging this expression for $x^*(w)$ into equation (5), we can solve for the supplier's pre-innovation value $V_0^s(w)$ and the pace of innovation as a function of the input price w:

$$V_0^s(w) = r + \frac{\pi_s(w_1)}{r} - \sqrt{r^2 + 2\Delta_s(w)} \qquad \text{and} \qquad x^*(w) = \sqrt{r^2 + 2\Delta_s(w)} - r,$$

where $\Delta_s(w) \equiv \pi^s(w_1) - \pi^s(w)$ is the incremental profit flow earned by the supplier when achieving the innovation.[11] Following similar steps, we can solve for the monopsonist's pre-innovation value: $V_0^m = (w - w^2 + x^s(w)V_1^m)/(x^s(w) + r)$. Finally, using the previous equations, we can replace the monopsonist's incremental value into the the monopsonist's optimal pricing condition in equation (7) and obtain

$$1 = 2w + \frac{w(\alpha^2/4 - (w - w^2))}{(\alpha^2/4 + r^2 - w^2)}.$$

This third-degree polynomial has three analytic solutions, but only one of them imply positive profits, quantities, and prices. We call this solution w_d, and is given by:

$$w_d = \frac{i\sqrt{3}-1}{2}C - \frac{i\sqrt{3}+1}{2}\frac{a + \frac{2r^2}{3}}{C}, \quad \text{where} \quad C = \frac{\sqrt[3]{\sqrt{\left(a+r^2\right)^2 - 4\left(a + \frac{2r^2}{3}\right)^3} - (a + r^2)}}{\sqrt[3]{2}},$$

$a = \alpha^2/4$, and i represents the imaginary number. Despite having an imaginary component, this solution takes values $w_d \in (1/3, 1/2]$ for every feasible value of α and r.

[11]In Marshall and Parra (2019), we show that the shape of the incremental profit flow with respect to the number of competitors determines the relationship between innovation and competition.

Full Vertical Integration In the context of assumptions (i) and (ii), the optimal production is $q_i^e = \alpha^i$, which implies that $\pi_i^{vi} \equiv R_i(q_i^e) - c(q_i^e) = \alpha^{2\cdot i}/2$ and $rV_1^{vi} = \pi_1^{vi}$. The first-order condition with respect to the R&D investment is $x_{vi} = V_1^{vi} - V_0^{vi}$. Plugging this expression for x_{vi} into equation (10), we can solve for the value of the vertically-integrated firm as well as the equilibrium R&D investment:

$$V_0^{vi} = r + \frac{\pi_1^{vi}}{r} - \sqrt{r^2 + 2\Delta_{vi}} \qquad \text{and} \qquad x_{vi} = \sqrt{r^2 + 2\Delta_{vi}} - r,$$

where $\Delta_{vi} = \pi_1^{vi} - \pi_0^{vi}$ is the incremental profit flow that the supplier earns when achieving the innovation.

Three separate firms The research lab must choose how much to invest in R&D given the transfer T. That is, the research lab solves

$$rL = \max_x \{-\kappa(x) + x(T - L)\},$$

where L is the value of the research lab before the innovation. The flow value of being an independent lab, rL, corresponds to the flow cost of R&D plus the incremental rent obtained from an innovation, $T - L$, which arrives at a rate $x_\ell(T)$. Under assumption (iii), the first-order condition with respect to the R&D investment becomes $x_\ell = T - L$. Using this expression we can then solve for the lab's value and its R&D investment as a function of T:

$$L = r + T - \sqrt{r^2 + 2rT} \qquad \text{and} \qquad x_\ell(T) = \sqrt{r^2 + 2rT} - r.$$

Given the lab's investment decision, we solve for the optimal transfer from the supplier's perspective. Let $\mathcal{V} = V_s^1 - S = \alpha/8 - S$, the optimal transfer to the lab T is found by solving the first order condition of problem (13):

$$\frac{r}{r + x_\ell(T)} \left(r(\mathcal{V} - 3T - r + \sqrt{r^2 + 2Tr}) \right) = 0.$$

This problem has two solutions, but only one leads to positive transfers for every feasible set of parameters:

$$T^*(S, \alpha, r) = \left(3\mathcal{V} - 2r + \sqrt{2r(2r + 3\mathcal{V}}) \right) \Big/ 9.$$

We can analytically solve for $\mathcal{V}$ (and S, as the value V_s^1 is known) by replacing the solution of T into (13). This leads to a polynomial of degree six that can be solved analytically. Only one of the solutions, however, makes economic sense:

$$\mathcal{V} = C_1 - \frac{12}{24} r - \left(\frac{3}{4}\Delta_{1,0} + \frac{215}{576} r^2 \right) / C_1,$$

where $\Delta_{1,0} = \pi_s(w_1) - \pi_s(w_0)$ and $C_1 > 0$ is equal to

$$C_1 = \frac{1}{24} \sqrt[3]{\frac{1}{r} \left(22248\Delta_{1,0} r^2 + 23328\Delta_{1,0}^2 + 5291 r^4 + 48\sqrt{6(14r^2 + 27\Delta_{1,0})^3 (r^2 + 2\Delta_{1,0})} \right)}.$$