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Technology Transfer in Global Value Chains

Abstract

Firm-to-firm relationships in global value chains create opportunities for North-South technology diffusion. This paper studies technology transfer in value chains when contracts are incomplete and input production technologies are imperfectly excludable. The paper introduces a new taxonomy of value chains based on whether or not the headquarters firm benefits from imitation of its supplier's technology. In inclusive value chains, where imitation is beneficial, the headquarters firm promotes technology diffusion. By contrast, in exclusive value chains headquarters seeks to limit supplier imitation. The paper analyzes how this distinction affects the returns to offshoring, the welfare effects of technical change and the social efficiency of knowledge sharing. Weaker intellectual property rights over input production technologies raise welfare when value chains are inclusive, but have the opposite effect under exclusive value chains.

JEL-Codes: D230, F100, F230, O340.

Keywords: technology transfer, global value chains, incomplete contracts, intellectual property rights, imitation.

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1 Introduction

The rise of global value chains during the 1990s and 2000s transformed the structure of industrial production, creating firm-to-firm relationships between buyers and suppliers that cross international borders (World Bank 2019). The mutual dependencies between producers within value chains mean that suppliers may benefit from value chain participation not only through securing a source of demand, but by receiving productivity-enhancing transfers of technology and other intangibles (Javorcik 2004; Alfaro-Ureña, Manelici and Vasquez 2019). Technology transfers within supply chains introduce new opportunities for development. Instead of building production capacity exclusively through domestic investment, belonging to global value chains may enable countries to short-circuit the development process by obtaining direct access to foreign technologies (Baldwin 2016).

Whether this potential is realized depends upon firms' incentives to invest in technology transfer and the extent to which technologies diffuse beyond value chains to the broader economy. Case studies document that although some headquarters firms seek to restrict diffusion of supply technologies, others invest substantial resources in developing broad-based supply capacities outside of their direct control.[1] Consequently, the impact of value chain participation on host countries varies greatly. Some value chains form enclaves with few links to the broader economy, while others promote the formation of clusters of independent suppliers.[2]

To formalize the role of global value chains in industrial development, this paper develops a theory of technology transfer in value chains. Central to the theory is the idea that value chains can be categorised based on whether or not supplier imitation increases the profits a headquarters firm makes from establishing a supply chain. In *inclusive* value chains, the headquarters firm benefits from imitation and has a incentive to encourage input technology diffusion and the emergence of supply clusters. By contrast, in *exclusive* value chains, imitation is costly for the headquarters firm, meaning it seeks to prevent diffusion and favors stronger intellectual property rights over input technologies. The paper begins by analyzing what determines whether value chains are inclusive or exclusive. It then uses the theory to show that optimal intellectual property policy, the effects of technical change and the efficiency of technology transfer investments differ depending upon whether value chains are inclusive or exclusive.

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[1] See World Bank (2019, Ch. 3), which discusses how the chip maker Synopsys has set-up degree programs in Armenia to train the microelectronics specialists needed by its suppliers, while the design of global value chains in the car and mining industries limits technology sharing.

[2] For example, Giuliani, Pietrobelli and Rabellotti (2005) document sectoral variation in how the characteristics of supply clusters affect technological upgrading in Latin American value chains.

The theory starts from the assumption that input production technologies are non-contractible, non-rival and imperfectly excludable. Incomplete contracts are at the heart of recent work explaining firm behavior in global value chains (Antràs 2003; Alfaro et al. 2019), while non-rivalry and partial excludability are the characteristics that distinguish technology from other production inputs (Romer 1990). The imperfect excludability of input technologies implies suppliers face an imitation risk.

Supplier imitation is conceptually distinct from technology diffusion through product imitation, which has been studied by the product cycle literature (Krugman 1979; Grossman and Helpman 1991) and in the context of value chains and firm boundaries by Bolatto et al. (2017) and Kukharskyy (2020). By fragmenting production across producers and locations, global value chains offer imitators the chance to learn and adopt input technologies without mastering the knowledge required for product imitation. And whereas product imitation is costly for imitated firms because it increases competition,[3] this paper shows that supplier imitation may either harm or benefit product owners.

Whether value chains are inclusive or exclusive depends upon how the risk of supplier imitation affects non-contractible investments. Incomplete contracts generate the hold-up problem identified by Grossman and Hart (1986), which leads to inefficiently low investment in technology transfer and input production (Acemoglu, Antràs and Helpman 2007). By introducing a potential alternative source of supply, imitation risk affects both the extent of under-investment and the division of the production surplus. Value chains are inclusive when imitation risk alleviates the hold-up inefficiencies and the resulting increase in production surplus exceeds the surplus captured by the imitator. Otherwise value chains are exclusive.

Formally, the paper models the problem faced by a headquarters firm that must hire an input supplier in order to produce. After hiring its supplier, the firm makes a knowledge transfer to the supplier, while the supplier invests in knowledge absorption. These technology investments jointly determine the supplier's productivity and are relationship-specific and non-contractible, as is the supplier's input production. However, before production takes place there is a risk that the supplier is imitated. When imitation occurs, the headquarters firm can source inputs from either its original supplier or the imitator.[4] Production decisions are the outcome of a cooperative game between the headquarters firm, its supplier and the imitator, and revenue sharing is determined by the Shapley value.

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[3] The concern that forced technology transfers harm US multinationals operating in China by eroding their competitive advantage has provided a major rationale for the US-China trade war initiated by President Trump (USTR 2018).

[4] Because the input technology is relationship-specific, the imitator can only supply the headquarters firm implying imitation does not affect product market competition. Allowing the imitator to supply the headquarters firm's competitors would introduce an additional cost of imitation.

Imitation risk affects the headquarters firm's expected profits through three channels. When imitation occurs, the headquarters firm cannot appropriate the entire expected surplus generated by its value chain, part of which is captured by the imitator leading to a loss of profits. At the production stage, the presence of an additional input supplier alleviates the hold-up inefficiency in input production, which boosts profits. Finally, the possibility of imitation affects both the headquarters firm's incentive to invest in knowledge transfer and its supplier's incentive to invest in knowledge absorption. How the change in incentives affects profits depends upon which investment is more important in determining supplier productivity. None of these channels exists in a complete contracting environment, where equilibrium profits and technology transfer are unaffected by imitation risk.

In equilibrium, three parameters determine if a value chain is inclusive or exclusive (or neither): the elasticity of final demand; the weight allocated to the headquarters firm's knowledge transfer in determining supplier productivity, and; the elasticity of technology investment costs. When the weight attached to headquarters' knowledge transfer is sufficiently high, imitation mitigates the hold-up inefficiency in technology investment by strengthening incentives for the headquarters firm relative to its supplier. This effect is stronger when the elasticity of technology investment costs is low, because a low elasticity makes technology transfer more sensitive to changes in investment incentives. In addition, a higher demand elasticity raises the returns to scale of the revenue function, which increases the benefits from alleviating the hold-up problem. Consequently, value chains are inclusive when demand is highly elastic and knowledge transfer is important relative to knowledge absorption in determining supplier productivity.

The second part of the paper applies the distinction between inclusive and exclusive value chains to study the equilibrium relationships between global value chains, technology diffusion and development. I embed the technology transfer problem into a general equilibrium model with free entry into innovation, which is required to create a headquarters firm, and into supplier imitation. I start by considering a closed economy and then analyze a North-South offshoring model where innovation is concentrated in the North and the South specializes in supplying inputs to Northern headquarters firms. I consider separately the case where value chains are inclusive and the case where value chains are exclusive.

Several insights emerge from the analysis. Suppose the cost of imitation in the South declines, due to either technical progress or policy changes that weaken intellectual property rights. All else constant, this shock increases imitation risk, which affects the profitability of offshoring and, consequently, factor incomes and welfare. However, the sign of these changes depends upon value chain type. When value chains are inclusive, a lower imitation cost increases real wages, whereas in exclusive value chains real wages decline. In the open economy model, a fall in imitation costs in the South also reduces the North-South wage gap if value chains are inclusive, but increases the gap if value chains are exclusive. These findings not only imply that optimal intellectual property policy differs depending upon whether value chains are inclusive or exclusive, but also suggest an explanation for why the relationship between value chain participation and development is context-dependent.

However, not all shocks have qualitatively different effects in inclusive versus exclusive supply chains. A fall in the cost of international technology transfer not only reduces imitation risk in the South, but also has a direct positive effect on supplier productivity in the South through increased technology investment. Independent of value chain type the latter effect dominates, meaning real wages rise in both countries and the Southern relative wage increases. The paper also shows that balanced global technical change, raises real wages in North and South without changing imitation risk or the wage gap. It follows that the bias (or lack thereof) of technical change matters for welfare and international inequality.

When allowed to establish either an inclusive or an exclusive value chain, headquarters firms use inclusive value chains only if the imitation cost is sufficiently low. Consequently, in an extension with many Southern countries, firms that offshore to high imitation cost countries use exclusive value chains, whereas firms that operate in low imitation cost countries operate inclusive value chains. Moreover, reducing imitation costs has a U-shaped effect on Southern real wages, which decline initially before increasing after the threshold for inclusive value chains is crossed.

The paper's final result shows that the sharing incentive that exists in inclusive value chains may generate beneficial spillovers to the broader economy that do not arise when value chains are exclusive. In the baseline model, headquarters firms' preferences over imitation risk are socially efficient regardless of value chain type. However, the alignment between private and social preferences relies on the assumption that knowledge spillovers only occur within supply chains. Relaxing this assumption, suppose headquarters firms choose between open or secret research, where open research increases imitation risk, but also generates spillovers that reduce entry costs for other innovators. With inclusive value chains firms opt for open research, which is socially efficient. By contrast, when value chains are exclusive secret research is chosen, which may reduce welfare if spillovers are sufficiently strong.[5] This mechanism provides a novel

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[5] Section 2.5 discusses an interesting caveat to the finding that headquarters firms want to reduce imitation risk in exclusive value chains. Although increasing the excludability of the supplier's technology is desirable ex-ante, once technology investments are sunk the headquarters firm stands to benefit from imitation. This creates a commitment problem due to time-inconsistency in the

rationalization for the hypothesis, implicit in much of the research on global value chains and development, that enclave value chains do not promote long-run growth.

This paper contributes to the existing literature along multiple dimensions. A substantial body of evidence shows that multinational firms act as a conduit for international technology transfers. Branstetter, Fisman and Foley (2006) and Bilir and Morales (2020) study technology transfers between US parent firms and their foreign affiliates. Javorcik (2004) and Blalock and Gertler (2008) provide industry-level evidence of productivity spillovers from foreign direct investment to upstream suppliers. Alfaro-Ureña, Manelici and Vasquez (2019) exploit rich data on firm-to-firm relationships in Costa Rica to show that domestic firms experience a productivity boost after becoming suppliers to foreign multinationals. Jiang et al. (2018) find that international joint ventures in China generate technology transfer to the joint venture partner and spillovers to other Chinese firms. This paper builds upon these empirical studies by developing a framework to understand technology transfer in global value chains and by characterizing the equilibrium consequences of offshoring and supplier imitation.

A large literature analyzes how incomplete contracts shape firm organization and intra-firm trade in global value chains (Antràs 2003; Antràs and Helpman 2004; Antràs and Chor 2013). Acemoglu, Antràs and Helpman (2007) consider the effect of incomplete contracts on headquarters firms' technology choices in a supply chain model. Bolatto et al. (2017) use the sequential production model of Antràs and Chor (2013) to analyze how intellectual property protection affects supply chain integration when producers face product imitation risk. Similarly, Kukharskyy (2020) studies how product knowledge appropriation affects the integration versus outsourcing decision in a version of the Antràs and Helpman (2004) model. However, previous work on value chains with incomplete contracts has not analyzed technology transfer between headquarters firms and their suppliers when input production technologies are imperfectly excludable. In particular, the existing literature has not drawn the distinction between inclusive and exclusive value chains.

Product cycle models have been used to analyze how intellectual property rights and foreign direct investment affect technology diffusion, wages and welfare (Helpman 1993; Lai 1998; Grossman and Lai 2004; Branstetter and Saggi 2011). Antràs (2005) also develops an incomplete contracts product cycle model in which standardization drives production offshoring. However, rather than analyzing vertical technology transfer, product cycle models restrict attention to horizontal technology diffusion between firms that compete in the same product market. This means that, even in models where weakening intellectual property

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headquarters firm's preferences.

rights is welfare increasing, product owners never have a sharing incentive.[6]

Vertical technology transfer in supply chains has been modelled by Pack and Saggi (2001), Goh (2005), Lin and Saggi (2007) and Carluccio and Fally (2013). Closest to this paper are the insightful models of Pack and Saggi (2001) and Goh (2005). Pack and Saggi (2001) argue that the effect of technology diffusion between suppliers on headquarters firms' profits is ambiguous and depends upon how diffusion affects competition in both the upstream and downstream markets. Goh (2005) extends Pack and Saggi's (2001) model to show that diffusion can reduce technology transfer when input quality is highly sensitive to supplier effort. Goh's (2005) result can be viewed as an example of this paper's finding that value chains are more likely to be exclusive when the supplier's technology investment is relatively more important. However, unlike this paper, both Pack and Saggi (2001) and Goh (2005) work in partial equilibrium and do not consider how incomplete contracts affect technology transfer incentives.

The remainder of the paper is organized as follows. Section 2 sets up and solves the technology transfer model in partial equilibrium. Section 3 embeds the model in general equilibrium for a closed economy. Section 4 introduces offshoring and analyzes how technological and institutional developments in the South affect incomes and welfare. Section 5 studies the circumstances under which private and social preferences over imitation risk are aligned. Finally, Section 6 concludes.

2 Technology Transfer Model

This section develops a theory of technology transfer within supply chains when contracts are incomplete and technologies are non-rival and imperfectly excludable. I start by analyzing technology transfer in partial equilibrium taking output demand, imitation risk and factor costs as given. Section 3 then embeds the technology transfer model in general equilibrium.

2.1 Value Chain

Consider a firm whose knowledge capital derives from ownership of a product blueprint. The blueprint confers the exclusive right to sell a product, together with knowledge of the process technology for making the firm's product. Demand for the product y is given by:

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[6] The welfare effects of intellectual property protection in product cycle models vary across papers and often hinge on general equilibrium effects that operate through the labor market clearing condition. See Saggi (2016) for a useful overview.

$$y = Ap^{-\sigma}, \tag{1}$$

where p denotes the price of output, A is a demand parameter that the firm takes as given and $\sigma > 1$ is the demand elasticity.

In order to produce, the headquarters firm needs to establish a value chain by hiring an input supplier. Suppose there are a large number of potential suppliers whose outside options have value zero and that the headquarters firm and the potential suppliers are risk neutral. Then the participation constraint implies that when the headquarters firm hires a supplier it receives an ex-ante transfer equal to the supplier's expected value of being hired. Through this payment the firm is able to capture the expected surplus accruing to the supplier from participating in the value chain.

When hired, the supplier has no relationship-specific technical knowledge. Consequently, before production occurs, it must learn how to produce the input used by the headquarters firm and this requires both the headquarters firm and the supplier to make technology transfer investments. The headquarters firm must invest in knowledge transfer to the supplier, while the supplier must invest in absorbing and learning the knowledge it receives. Using h subscripts to denote the headquarters firm and m the supplier, let z_h be the investment in knowledge transfer made by the headquarters firm and z_m be the supplier's investment in knowledge absorption. The supplier's technology z is:

$$z = z_h^{\gamma} z_m^{1-\gamma},$$

where $\gamma \in [0, 1]$ controls the relative importance of the headquarters firm's investment in determining the supplier's technology. I will refer to γ as the knowledge transfer share. The case where $\gamma = 1$ yields a pure *knowledge transfer* model in which the supplier's technology is entirely determined by the knowledge transfer made by the headquarters firm. But if $\gamma < 1$ the supplier's own investment also affects its technology and the case with $\gamma = 0$ gives a pure *supplier learning* model of technology transfer.

Technology transfer is costly. To make a knowledge transfer investment z_h, the headquarters firm must hire $f_h z_h^{\delta}$ workers at wage w_h. Likewise, investing z_m in knowledge absorption requires the supplier to hire $f_m z_m^{\delta}$ workers at wage w_m. This set-up allows for the possibility that $w_h \neq w_m$ since the headquarters firm may hire a foreign supplier. The parameters f_h and f_m determine the costs of technology transfer. A reduction in f_h corresponds to an increase in the efficiency of headquarters' knowledge transfer, while a lower f_m can be interpreted as an improvement in suppliers' knowledge absorption capacities. In the general equilibrium offshoring model these parameters will vary by country and depend upon whether technology transfer is domestic or international.

The parameter δ gives the elasticity of technology transfer costs to the investments z_h and z_m made by the headquarters firm and supplier, respectively. A higher δ makes technology transfer more costly, leading to supply chains that are less technology intensive. I assume $\delta > \sigma - 1$, which is sufficient to ensure that the headquarters firm and the supplier face concave optimization problems when choosing z_h and z_m.

After technology transfer has taken place, the supplier produces inputs using labor. Input production y_m is given by $y_m = zl_m$, where l_m denotes the supplier's employment of production workers. Because the inputs are relationship-specific they have no value outside the supplier-firm relationship, but the headquarters firm can transform inputs one-to-one into output at zero cost.

In a complete contracting environment, the distinction between the headquarters firm and its supplier would be immaterial, but in this economy contracts are incomplete. Specifically, I assume the supplier's input production, the headquarters' knowledge transfer investment and the supplier's knowledge absorption investment are non-contractible. This means they will not be chosen to maximize the joint surplus generated by the firm-supplier relationship. Instead, there will be a hold-up problem and the headquarters firm and its supplier will optimize independently. Consequently, their behavior will depend upon the sequencing of decisions and upon how sales revenue is shared between them. However, before discussing revenue sharing there is an additional feature of the model that needs to be introduced: the supplier's technology is imperfectly excludable and may be imitated.

2.2 Imitation

Suppose that with exogenous probability q an imitator is able to copy and adopt the supplier's process technology. Imitation occurs after the headquarters firm and the supplier have made their technology transfer investments, but before any production takes place. A successful imitator learns how to produce the headquarters firm's input using the same technology z as the supplier. Therefore, the imitator's input production technology is $y_g = zl_g$ where g subscripts denote the imitator. Assume also that the supplier and the imitator produce the same homogeneous input and that the imitator is based in the same country as the supplier, implying it faces the same wage rate $w_g = w_m$.

When imitation occurs, the headquarters firm has the opportunity to source inputs from the imitator as well as (or instead of) the supplier, meaning that the firm and supplier no longer have a bilateral monopoly over the production process. Instead there are three players and I assume that they form a coalition to maximize the joint surplus of their relationship and that the division of surplus between the participants is given by the Shapley value (Shapley 1953).[7] Since technology transfer and input production occur prior to coalition formation, the coalition's surplus equals the revenue generated by output sales, which from the demand equation (1) is given by $py = A^{\frac{1}{\sigma}} y^{\frac{\sigma-1}{\sigma}}$. It follows that the joint surplus is maximized when the headquarters firm uses all available inputs to produce output $\tilde{y} = \tilde{y}_m + \tilde{y}_g$ where a tilde is used to denote outcomes under imitation.

When the supplier is not imitated, I continue to assume that the players maximize their joint surplus and that the surplus is divided according to the Shapley value. But without imitation the coalition only has two players – the headquarters firm and the supplier – and output is given by $y = y_m$. In this case, the Shapley value allocation is equivalent to Nash bargaining with symmetric bargaining weights implying that the headquarters and the supplier each receives one-half of the sales revenue.

This completes the specification of the partial equilibrium model. Note that production has five stages as illustrated in Figure 1. In stage one the headquarters firm hires a supplier and receives a payment from its chosen supplier. At stage two the headquarters firm and its supplier make independent technology transfer investments. The headquarters invests in transferring its process technology to the supplier and the supplier invests in absorbing the technology. At stage three imitation occurs with probability q. In stage four the supplier and the imitator (if imitation has taken place at stage three) choose what input quantities to produce. Finally, in stage five the headquarters firm, supplier and imitator (if one exists) cooperate to maximize their joint surplus and the division of surplus is determined by the Shapley value. Hold-up problems arise due to the non-contractible relationship-specific investments made at both stage two and stage four.

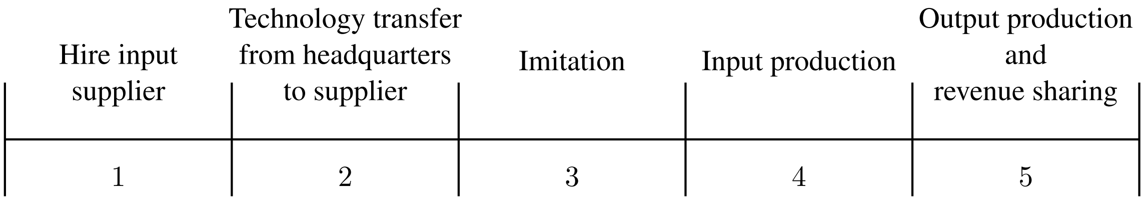

Figure 1: Stages of production

Before solving for the equilibrium, it is worth discussing in more detail three assumptions that are

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[7] Acemoglu, Antràs and Helpman (2007) also use the Shapley value to determine the division of surplus when a firm has multiple suppliers.

embedded in the model. First, there is no product imitation. A large literature studies how product imitation drives product cycles in open economies (Krugman 1979; Grossman and Helpman 1991), but less attention has been paid to imitation that affects upstream stages of the value chain while leaving intact the product owner's monopoly over sales of final output. Consequently, the model abstracts from product imitation to better highlight the novel mechanisms that emerge when imitation targets suppliers. Second, the model does not allow the headquarters firm to affect the allocation of property rights by choosing to integrate its supplier in stage one. Understanding how incomplete contracts affect the organization of firms has been the main objective of the property rights literature (Grossman and Hart 1986; Hart and Moore 1990; Antràs 2003), but the model simplifies along this dimension in order to focus on the technology transfer decision.

Finally, Section 2.4 below shows that, because of the hold-up problem between headquarters and supplier, the headquarters firm may benefit from having more than one supplier. However, I assume that the costs of technology transfer are sufficiently large that it is never optimal for the firm to hire multiple suppliers at stage one. This assumption captures the idea that, after one supplier has learnt how to produce the input used by the headquarters firm, imitation provides a less costly source of additional input supply than further investment in technology transfer.

2.3 Complete Contracts Equilibrium

As a reference point, it is useful to start by solving for the equilibrium with complete contracts. In this case, the contract between the headquarters firm and its supplier will be designed to maximize the surplus created from all stages of production and to ensure that the entire surplus is captured by the headquarters as profits π_h. Moreover, since the supplier and any imitator produce a homogenous input and have the same constant returns to scale production technology, there is no incentive for the headquarter's firm to trade with the imitator and the returns to imitation are zero. Consequently, the complete contracts equilibrium is independent of the imitation probability q. In fact, because input production occurs after imitation, input contractibility is sufficient for the equilibrium to be independent of q even if the technology investments are non-contractible.

Formally, the complete contracts equilibrium is given by solving:

$$\max_{z_h, z_m, y} \pi_h = A^{\frac{1}{\sigma}} y^{\frac{\sigma-1}{\sigma}} - \frac{y}{z_h^{\gamma} z_m^{1-\gamma}} w_m - f_h z_h^{\delta} w_h - f_m z_m^{\delta} w_m,$$

where the objective function is the difference between revenue and the combined costs of input production and technology transfer. Solving and using c superscripts to denote outcomes with complete contracts yields:

$$\begin{aligned}
z_h^c &= \left[\left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\frac{1}{\delta}\frac{A}{w_m^{\sigma-1}}\left(\frac{\gamma}{f_h w_h}\right)^{\frac{\delta-(1-\gamma)(\sigma-1)}{\delta}}\left(\frac{1-\gamma}{f_m w_m}\right)^{\frac{(1-\gamma)(\sigma-1)}{\delta}}\right]^{\frac{1}{\delta+1-\sigma}}, \\
z_m^c &= \left(\frac{1-\gamma}{\gamma}\frac{f_h}{f_m}\frac{w_h}{w_m}\right)^{\frac{1}{\delta}} z_h^c, \\
y^c &= \left(\frac{\sigma-1}{\sigma}\right)^{\sigma} A\left[\frac{\left(z_h^c\right)^{\gamma}\left(z_m^c\right)^{1-\gamma}}{w_m}\right]^{\sigma}, \\
\pi_h^c &= \frac{\delta+1-\sigma}{\sigma-1}\left[\left(\frac{\sigma-1}{\sigma}\right)^{\sigma}\frac{1}{\delta}\frac{A}{w_m^{\sigma-1}}\left(\frac{\gamma}{f_h w_h}\right)^{\frac{\gamma(\sigma-1)}{\delta}}\left(\frac{1-\gamma}{f_m w_m}\right)^{\frac{(1-\gamma)(\sigma-1)}{\delta}}\right]^{\frac{\delta}{\delta+1-\sigma}}.
\end{aligned} \tag{2}$$

Headquarters' knowledge transfer investment, the supplier's knowledge absorption investment, output and profits are increasing in demand A and decreasing in labor costs w_h and w_m and in the technology transfer cost parameters f_h and f_m.

2.4 Incomplete Contracts Equilibrium

I will solve for a subgame perfect Nash equilibrium of the incomplete contracts economy using backward induction.

Revenue sharing

In stage five, the headquarters firm transforms all available inputs into output and sales revenue is allocated according to the Shapley value. Each player's Shapley value equals the average over all possible orderings of the players of its marginal contribution to the value of its coalition with the preceding players in the ordering. Consider first the case with imitation. In this case there are three players and six possible orderings. Any coalition that does not involve the headquarters firm has value zero because the inputs are relationship-specific and can only be used by headquarters. A coalition between the headquarters firm and the supplier can produce output $\tilde{y}_m$, while a coalition between headquarters and the imitator can produce output $\tilde{y}_g$. Finally, the grand coalition produces output $\tilde{y} = \tilde{y}_m + \tilde{y}_g$. Let $\tilde{V}_i$ denote the Shapley value of player $i = h, m, g$. Averaging over all orderings of the players implies:

$$\tilde{V}_h = \frac{A^{\frac{1}{\sigma}}}{6}\left[2\left(\tilde{y}_m + \tilde{y}_g\right)^{\frac{\sigma-1}{\sigma}} + \tilde{y}_m^{\frac{\sigma-1}{\sigma}} + \tilde{y}_g^{\frac{\sigma-1}{\sigma}}\right],$$
$$\tilde{V}_m = \frac{A^{\frac{1}{\sigma}}}{6}\left[2\left(\tilde{y}_m + \tilde{y}_g\right)^{\frac{\sigma-1}{\sigma}} + \tilde{y}_m^{\frac{\sigma-1}{\sigma}} - 2\tilde{y}_g^{\frac{\sigma-1}{\sigma}}\right],$$
$$\tilde{V}_g = \frac{A^{\frac{1}{\sigma}}}{6}\left[2\left(\tilde{y}_m + \tilde{y}_g\right)^{\frac{\sigma-1}{\sigma}} - 2\tilde{y}_m^{\frac{\sigma-1}{\sigma}} + \tilde{y}_g^{\frac{\sigma-1}{\sigma}}\right].$$

Note that $\tilde{V}_h + \tilde{V}_m + \tilde{V}_g$ equals sales revenue $A^{\frac{1}{\sigma}}\left(\tilde{y}_m + \tilde{y}_g\right)^{\frac{\sigma-1}{\sigma}}$.

When there is no imitation, revenue $A^{\frac{1}{\sigma}} y_m^{\frac{\sigma-1}{\sigma}}$ is shared equally between the headquarters firm and the supplier and the Shapley values are:

$$V_h = V_m = \frac{1}{2} A^{\frac{1}{\sigma}} y_m^{\frac{\sigma-1}{\sigma}}.$$

Comparing the Shapley values with and without imitation shows that imitation increases the headquarters firm's revenue share, but decreases the supplier's revenue share.[8] This occurs because the imitator provides competition to the supplier, while also creating an outside option for the headquarters firm. However, because input production levels may differ in the two cases, knowing how revenue shares change is not sufficient to draw conclusions about changes in payoffs.

Input production

At stage four, the supplier chooses input quantity to maximize its payoff taking its technology z and whether it has been imitated as given. The supplier's payoff equals the difference between its Shapley value and its input production costs. Therefore, in the event of imitation the supplier's problem is:

$$\max_{\tilde{y}_m} \ \tilde{V}_m^* = \tilde{V}_m - \frac{\tilde{y}_m}{z} w_m,$$

where $\tilde{V}_m^*$ denotes the supplier's payoff from stage four onwards. When there is no imitation the supplier chooses y_m to maximize $V_m^* = V_m - y_m w_m / z$. Likewise, when imitation occurs, the imitator chooses $\tilde{y}_g$ to maximize $\tilde{V}_g^* = \tilde{V}_g - \tilde{y}_g w_m / z$. Solving, and noting that when imitation occurs the supplier and imitator

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[8] To see this note that $\tilde{y}_m^{\frac{\sigma-1}{\sigma}} + \tilde{y}_g^{\frac{\sigma-1}{\sigma}} > \left(\tilde{y}_m + \tilde{y}_g\right)^{\frac{\sigma-1}{\sigma}}$ implying that under imitation the headquarters firm has a revenue share greater than one-half.

are symmetric, yields:

$$\begin{aligned}\tilde{y}_m = \tilde{y}_g &= \left(\frac{1+2^{\frac{\sigma-1}{\sigma}}}{6}\right)^{\sigma} A \left(\frac{\sigma-1}{\sigma}\right)^{\sigma} \left(\frac{z}{w_m}\right)^{\sigma}, \\ y_m &= \frac{1}{2^{\sigma}} A \left(\frac{\sigma-1}{\sigma}\right)^{\sigma} \left(\frac{z}{w_m}\right)^{\sigma}.\end{aligned} \tag{3}$$

These equations show that $\tilde{y}_m < y_m < \tilde{y}_m + \tilde{y}_g$ implying imitation reduces the supplier's input production, while increasing total input production and output. The hold-up problem due to incomplete input contracts means the supplier's input production is below the efficient level that maximizes production surplus. By increasing output, imitation reduces this inefficiency. However, holding z constant, total output is still inefficiently low since $\tilde{y}_m + \tilde{y}_g < y^c$ where the complete contracts output level y^c is given by (2).

Using the solutions for optimal input production, the stage four payoffs can be written as:

$$\begin{aligned}\tilde{V}_i^* &= \frac{\tilde{\alpha}_i}{\sigma} \left(\frac{\sigma-1}{\sigma}\right)^{\sigma-1} A \left(\frac{z}{w_m}\right)^{\sigma-1}, \qquad i = h, m, g, \\ V_i^* &= \frac{\alpha_i}{\sigma} \left(\frac{\sigma-1}{\sigma}\right)^{\sigma-1} A \left(\frac{z}{w_m}\right)^{\sigma-1}, \qquad i = h, m,\end{aligned} \tag{4}$$

where:

$$\begin{aligned}\tilde{\alpha}_h &= \sigma \left(\frac{1+2^{-\frac{\sigma-1}{\sigma}}}{3}\right)^{\sigma}, \ \alpha_h = \frac{\sigma}{2^{\sigma}}, \ \alpha_m = \frac{1}{2^{\sigma}}, \\ \tilde{\alpha}_m = \tilde{\alpha}_g &= \frac{1}{6^{\sigma}} \left(1+2^{\frac{\sigma-1}{\sigma}}\right)^{\sigma-1} \left[1+2^{\frac{\sigma-1}{\sigma}} - \sigma\left(2-2^{\frac{\sigma-1}{\sigma}}\right)\right].\end{aligned}$$

The payoffs with and without imitation differ only through variation in the α coefficients, which I will refer to as the payoff coefficients. It is straightforward to show that $1 > \tilde{\alpha}_h > \alpha_h > \alpha_m > \tilde{\alpha}_m$.[9] Imitation introduces a second source of inputs, which increases the headquarters firm's stage four payoff, but reduces the supplier's payoff. The effect of imitation on their combined payoff is ambiguous and depends upon the elasticity of demand σ. On the one hand imitation mitigates the hold-up inefficiency by increasing production, but on the other hand part of the increased surplus is captured by the imitator, which makes profits $\pi_g = \tilde{V}_g^*$. As demand becomes more elastic, the hold-up inefficiency becomes more costly and the share of surplus captured by the imitator declines. Consequently, $\frac{\tilde{V}_h^* + \tilde{V}_m^*}{V_h^* + V_m^*} = \frac{\tilde{\alpha}_h + \tilde{\alpha}_m}{\alpha_h + \alpha_m}$ is strictly increasing in

---

[9] The key to proving these inequalities is to observe that $1 < 2^{\frac{\sigma-1}{\sigma}} < 2$ and that $\sigma^{\frac{1}{\sigma}} < 3/2$ when $\sigma > 1$.

σ as shown in Figure 2. The negative effect of imitation on the combined payoff dominates for low σ, while the positive effect dominates for σ above approximately 2.3.

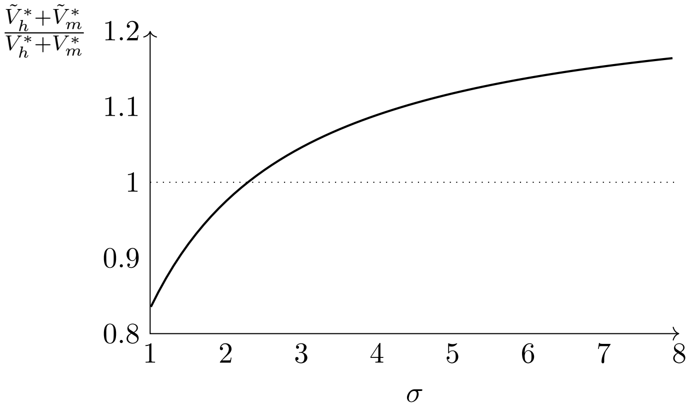

Figure 2: Imitation and stage four payoffs

All stage four payoffs also depend on the supplier's technology z; the next step in solving the model is to endogenize z.

Technology transfer

At stage two, the headquarters firm chooses the knowledge transfer z_h it makes to the supplier without knowing whether imitation will occur in stage three. Consequently, z_h is chosen to maximize its expected payoff taking the imitation probability q and the supplier's technology investment z_m as given:

$$\max_{z_h} \hat{V}_h = (1-q)V_h^* + q\tilde{V}_h^* - f_h w_h z_h^\delta,$$

where $\hat{V}_h$ denotes the headquarters firm's expected payoff from stage two onwards, which equals its expected stage four payoff net of knowledge transfer costs. At the same time, the supplier's technology investment z_m is chosen to maximize:

$$\max_{z_m} \hat{V}_m = (1-q)V_m^* + q\tilde{V}_m^* - f_m w_m z_m^\delta.$$

Recalling that $z = z_h^\gamma z_m^{1-\gamma}$, these optimization problems can be solved using the stage four payoffs derived above. This gives the Nash equilibrium for the optimal investments in knowledge transfer and knowledge absorption:

$$
\begin{aligned}
z_h &= \left[\left(\frac{\sigma - 1}{\sigma} \right)^{\sigma} \frac{1}{\delta} \frac{A}{w_m^{\sigma-1}} \left(\frac{\gamma \hat{\alpha}_h}{f_h w_h} \right)^{\frac{\delta-(1-\gamma)(\sigma-1)}{\delta}} \left(\frac{(1-\gamma)\,\hat{\alpha}_m}{f_m w_m} \right)^{\frac{(1-\gamma)(\sigma-1)}{\delta}} \right]^{\frac{1}{\delta+1-\sigma}}, \\
z_m &= \left(\frac{1-\gamma}{\gamma} \frac{\hat{\alpha}_m}{\hat{\alpha}_h} \frac{f_h}{f_m} \frac{w_h}{w_m} \right)^{\frac{1}{\delta}} z_h,
\end{aligned}
\tag{5}
$$

where:

$$
\hat{\alpha}_i = (1-q)\alpha_i + q\tilde{\alpha}_i = \alpha_i + q\left(\tilde{\alpha}_i - \alpha_i\right), \qquad i = h, m, \tag{6}
$$

is the expected value of player i's payoff coefficient in stage four. Since $\tilde{\alpha}_h > \alpha_h$, the headquarters firm's expected payoff coefficient is strictly increasing in the imitation probability q, while the supplier's expected payoff coefficient is decreasing in q because $\tilde{\alpha}_m < \alpha_m$.

Comparing technology investments under incomplete contracts (equation 5) and under complete contracts (equation 2) shows that the effect of incomplete contracts operates exclusively through the expected payoff coefficients. Technology investments in the complete contracts equilibrium are obtained by setting the expected payoff coefficients equal to one. Since $1 > \hat{\alpha}_h > \hat{\alpha}_m$, it follows that the hold-up problem reduces the headquarters firm's knowledge transfer. Moreover, because $\hat{\alpha}_m < \hat{\alpha}_h$, the ratio z_m/z_h is lower than with complete contracts implying that the supplier under invests by more than the headquarters firm.

Using (5), the supplier's equilibrium technology is given by:

$$
z = \left[\left(\frac{\sigma - 1}{\sigma} \right)^{\sigma} \frac{1}{\delta} \frac{A}{w_m^{\sigma-1}} \left(\frac{\gamma \hat{\alpha}_h}{f_h w_h} \right)^{\gamma} \left(\frac{(1-\gamma)\,\hat{\alpha}_m}{f_m w_m} \right)^{1-\gamma} \right]^{\frac{1}{\delta+1-\sigma}}, \tag{7}
$$

and differentiating this equation with respect to q yields:

$$
\frac{1}{z}\frac{\partial z}{\partial q} = \frac{1}{\delta + 1 - \sigma} \left[\frac{\gamma\left(\tilde{\alpha}_h - \alpha_h\right)}{\hat{\alpha}_h} + \frac{(1-\gamma)\left(\tilde{\alpha}_m - \alpha_m\right)}{\hat{\alpha}_m} \right].
$$

The first term on the right hand side of this expression is positive, while the second term is negative. An increase in imitation risk raises the headquarters firm's expected payoff coefficient, which leads to higher technology transfer investments by both the headquarters firm and the supplier. However, a higher q also decreases the supplier's expected payoff coefficient, thereby reducing z_h and z_m.

Which effect dominates depends upon γ, the knowledge transfer share. It is straightforward to show that there exist thresholds γ_1^*, γ_2^* with $0 < \gamma_1^* < \gamma_2^* < 1$ such that the positive effect always dominates if $\gamma \geq \gamma_2^*$, while the negative effect always dominates if $\gamma \leq \gamma_1^*$.[10] For example, in a pure knowledge transfer model with $\gamma = 1$, higher imitation risk always increases z. By contrast, in the opposite extreme where $\gamma = 0$ and there is no knowledge transfer, greater imitation risk reduces z. For intermediate cases with $\gamma_1^* < \gamma < \gamma_2^*$, supplier productivity z is inverse U-shaped as a function of q. Lemma 1 summarizes this result.

Lemma 1. *There exists* $0 < \gamma_1^* < \gamma_2^* < 1$ *such that:*
(i) If $\gamma \leq \gamma_1 *$ *higher imitation risk reduces supplier productivity; (ii) If* $\gamma \geq \gamma_2 *$ *higher imitation risk increases supplier productivity; (iii) If* $\gamma_1^* < \gamma < \gamma_2^*$ *then supplier productivity is inverse-U shaped in the risk of imitation.*

Lemma 1 implies that, when contracts are incomplete, the effect of imitation risk on supplier productivity depends qualitatively upon the knowledge transfer share γ. An increase in the imitation probability raises the headquarters firm's expected payoff coefficient, while hurting the supplier. Therefore, the net effect of higher imitation risk on the supplier's technology is positive only when the technology transfer investment made by the headquarters firm is sufficiently important relative to the supplier's investment.

Models of firm organization under incomplete contracts find it is optimal to allocate residual property rights to the party making the more important relationship-specific investment (Antràs 2003). Lemma 1 relates to this finding since imitation affects relationship-specific investment incentives in an analogous manner to changing property rights. But imitation is not isomorphic to a change in property rights because, in addition to affecting investment incentives, imitation leads to technology diffusion. Consequently, when imitation occurs the headquarters firm cannot appropriate the entire production surplus. The final step in characterizing the incomplete contracts equilibrium is to solve for the headquarters firm's expected profits.

Profits

When the headquarters firm sets-up its supply chain at stage one, the supplier's participation constraint is binding. Since the supplier is risk neutral and has zero outside option, this implies that the supplier makes an ex-ante transfer to the headquarters firm equal to its expected payoff from stage two onwards $\hat{V}_m$. The headquarters firm's expected profits from its supply chain are therefore given by $\pi_h = \hat{V}_h + \hat{V}_m$. Using (5) to solve for the expected payoffs yields:

---

[10] To be specific, $\gamma_1^* = \frac{\alpha_h(\alpha_m - \tilde{\alpha}_m)}{\tilde{\alpha}_h \alpha_m - \alpha_h \tilde{\alpha}_m}$ and $\gamma_2^* = \frac{\tilde{\alpha}_h(\alpha_m - \tilde{\alpha}_m)}{\tilde{\alpha}_h \alpha_m - \alpha_h \tilde{\alpha}_m}$.

$$\pi_h = \frac{\hat{\alpha}_h \left[\delta - \gamma(\sigma-1)\right] + \hat{\alpha}_m \left[\delta - (1-\gamma)(\sigma-1)\right]}{\sigma - 1} \\ \times \left[\left(\frac{\sigma-1}{\sigma} \right)^{\sigma} \frac{1}{\delta} \frac{A}{w_m^{\sigma-1}} \left(\frac{\gamma \hat{\alpha}_h}{f_h w_h} \right)^{\frac{\gamma(\sigma-1)}{\delta}} \left(\frac{(1-\gamma)\hat{\alpha}_m}{f_m w_m} \right)^{\frac{(1-\gamma)(\sigma-1)}{\delta}} \right]^{\frac{\delta}{\delta+1-\sigma}} . \tag{8}$$

Profits π_h are increasing in the level of demand A and decreasing in the headquarters firm's wage w_h, the supplier's wage w_m and the technology investment cost parameters f_h and f_m.

Comparing π_h to complete contracts profits π_h^c in equation (2) shows that, as at stage two, the effect of incomplete contracts on equilibrium outcomes operates through the expected payoff coefficients. And since $\hat{\alpha}_h + \hat{\alpha}_m < 1$,[11] profits under incomplete contracts are lower than profits under complete contracts $\pi_h < \pi_h^c$. Expected profits are lower with incomplete contracts because: (i) imitation prevents the headquarters firm from capturing all the production surplus; (ii) input production is lower conditional on the supplier's technology and; (iii) the supplier has an inferior technology. The first channel affects the allocation of the production surplus, while the second and third channels reduce efficiency.

At this point, it is useful to introduce the following taxonomy of supply chains.

Definition 1. *A value chain is:*

(i) Inclusive when expected profits π_h are strictly increasing in the imitation probability q for all $q \in [0,1]$;

(ii) Exclusive when expected profits π_h are strictly decreasing in the imitation probability q for all $q \in [0,1]$.

When a value chain is inclusive the headquarters firm benefits from an increase in imitation risk, whereas in an exclusive value chain the opposite is true.

Whether value chains are inclusive or exclusive is, in general, ambiguous. The second term on the right hand side of the profit equation (8) is proportional to $z^{\sigma-1}$, while the first term depends upon imitation risk through $SC \equiv \hat{\alpha}_h \left[\delta - \gamma(\sigma-1)\right] + \hat{\alpha}_m \left[\delta - (1-\gamma)(\sigma-1)\right]$, which determines the value the firm obtains from its supply chain conditional on demand, factor costs and the supplier's technology. Therefore, differentiating (8) with respect to q gives:

---

[11] Since $\sigma > 1$, both $\alpha_h + \alpha_m < 1$ and $\tilde{\alpha}_h + \tilde{\alpha}_m < 1$.

$$
\begin{aligned}
\frac{1}{\pi_h}\frac{\partial \pi_h}{\partial q} \equiv \chi &= \frac{1}{SC}\frac{\partial SC}{\partial q} + (\sigma-1)\frac{1}{z}\frac{\partial z}{\partial q}, \\
&= \frac{(\tilde{\alpha}_h-\alpha_h)\left[\delta-\gamma(\sigma-1)\right]+(\tilde{\alpha}_m-\alpha_m)\left[\delta-(1-\gamma)(\sigma-1)\right]}{\hat{\alpha}_h\left[\delta-\gamma(\sigma-1)\right]+\hat{\alpha}_m\left[\delta-(1-\gamma)(\sigma-1)\right]} \qquad (9)\\
&+ \frac{\sigma-1}{\delta+1-\sigma}\left[\frac{\gamma\left(\tilde{\alpha}_h-\alpha_h\right)}{\hat{\alpha}_h}+\frac{(1-\gamma)\left(\tilde{\alpha}_m-\alpha_m\right)}{\hat{\alpha}_m}\right]. \qquad (10)
\end{aligned}
$$

Inspection of this expression shows that higher imitation risk may either raise or lower profits because of the trade-off between an increase in $\hat{\alpha}_h$ and a reduction in $\hat{\alpha}_m$.[12] In addition, the sign of the profit derivative χ depends upon only three model parameters: the demand elasticity σ; the technology transfer cost elasticity δ, and; the knowledge transfer share γ. Although, as χ is also a function of imitation risk, its sign can vary with q meaning that some value chains are neither inclusive nor exclusive.

The parameters σ, γ and δ determine the relative strengths of the channels identified above through which imitation risk affects expected profitability. Imitation prevents the headquarters firm from appropriating the entire production surplus, which reduces profits. However, it also has a positive effect on profits by alleviating the hold-up inefficiency in input production at stage four. As shown in Figure 2, this benefit more than offsets the expected loss in surplus to the imitator provided σ is sufficiently high because a high demand elasticity raises the returns to scale of the revenue function.

An increase in q strengthens technology investment incentives for the headquarters firm relative to its supplier. Whether this change mitigates or exacerbates under-investment at stage two depends upon the knowledge transfer share γ, as described in Lemma 1. When γ is sufficiently high it is desirable to give stronger incentives to the headquarters firm, meaning that productivity is increasing in imitation risk. But for low γ higher imitation risk reduces productivity. Regardless of the sign of this relationship, the magnitude of the technology investment effect is greater when investments are more responsive to changes in expected payoffs, which occurs when the investment cost elasticity δ is small relative to σ (see equation 7).

Figure 3 uses equation (9) to classify value chains in (σ, δ) space for three cases: a pure knowledge transfer model with $\gamma = 1$ in panel (a); a pure supplier learning model with $\gamma = 0$ in panel (b), and; an intermediate case with $\gamma = 1/2$ in panel (c).

In the knowledge transfer model with $\gamma = 1$, an increase in imitation risk improves the supplier's

---

[12] To see this note that $\frac{\partial z}{\partial q}$ may be positive or negative by Lemma 1. Also, for $\delta + 1 - \sigma$ sufficiently close to zero $\frac{\partial SC}{\partial q}$ is positive when $\gamma = 0$ and negative when $\gamma = 1$.

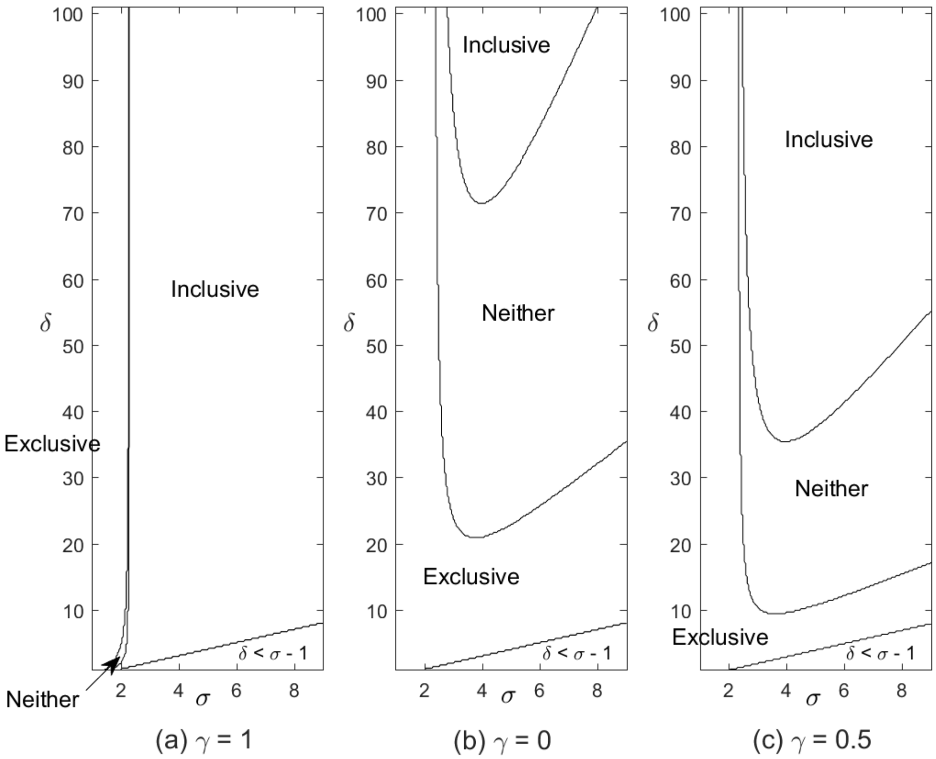

Figure 3: Classification of value chain types

technology. Consequently, in panel (a) either a high σ or a low σ combined with a sufficiently low δ ensures the value chain is inclusive. By contrast, in the supplier learning case where $\gamma = 0$ shown in panel (b), higher imitation risk reduces the supplier's technology. As a result, the set of inclusive value chains shrinks compared to panel (a) and the value chain is exclusive if either σ is low or δ is low.

The same mechanisms operate for intermediate values of γ with the role of δ dependent on how imitation risk affects the supplier's technology. In the case with $\gamma = 1/2$, higher imitation risk has a negative effect on the supplier's technology. Consequently, the value chain classification in panel (c) is qualitatively similar to the classification for the supplier learning model in panel (b). However, a higher γ mitigates the negative effect of imitation risk on the supplier's technology, which expands the set of parameter values that yield inclusive value chains relative to panel (b).

To summarize: (i) all value chains with sufficiently low demand elasticity σ are exclusive; (ii) an increase in the knowledge transfer share γ tends to expand the set of inclusive value chains in (σ, δ) space, and; (iii) the effect of changes in the investment cost elasticity δ is ambiguous and depends upon whether higher imitation risk increases the supplier's productivity.

2.5 Intellectual Property Rights

In an inclusive value chain the headquarters firm has a "sharing" incentive to encourage imitation of the input production technology. By contrast, in an exclusive value chain the firm has a "secrecy" incentive to limit imitation. This distinction has important implications for how firms treat intellectual property.

Suppose the headquarters firm has the opportunity to patent its input production technology at no cost. Taking out a patent increases the excludability of the supplier's technology, which, provided the patent is enforced at stage three, reduces imitation risk q. In an inclusive value chain the headquarters firm will not seek to enforce its intellectual property rights because its profits are increasing in q.

By contrast, in an exclusive value chain the firm stands to benefit from a reduction in imitation risk. However, an interesting wrinkle emerges in this case because the headquarters firm's preferences over imitation risk are not consistent across production stages. Ex-ante, at stage one, profits π_h are decreasing in q. But it was shown above that from stage four onwards the firm's payoff is always higher under imitation $\tilde{V}_h^* > V_h^*$. Therefore, if the headquarters firms can choose at stage three whether to enforce its patent, it will not enforce its rights even though this behavior reduces its expected profits at stage one (because the supplier anticipates non-enforcement). A commitment device is needed to resolve the time-inconsistency problem. For example, the headquarters firm could patent the input production technology before establishing a supply chain and then transfer its intellectual property rights to the supplier at stage one. Since $\tilde{V}_m^* < V_m^*$, the supplier would always choose to enforce the patent at stage three. Lemma 2 summarizes patenting behavior.

Lemma 2. *In an inclusive value chain the headquarters firm will not patent its input production technology. In an exclusive value chain the headquarters firm will patent the input production technology and transfer ownership of the patent to the supplier when setting-up the value chain.*

Legal rights over intellectual property are not the only avenue through which the headquarters firm and its supplier may seek to affect the excludability of the supplier's technology and, thereby, change imitation risk. For example, suppose the headquarters firm can reduce imitation risk by choosing to own its supplier rather than outsourcing. All else equal, this creates an incentive to integrate exclusive value chains and outsource inclusive value chains.

3 Value Chains in Equilibrium

This section embeds the theory of technology transfer developed above into a general equilibrium supply chain model. I use the model to study how technical change affects production, productivity, wages and consumption when production occurs within supply chains.

3.1 Model Set-up

Consider a closed economy with population L. There is a single consumption good that is produced under perfect competition from differentiated products using a constant elasticity of substitution production technology defined by:

$$C = \left(\int_{\omega \in \Omega} y(\omega)^{\frac{\sigma-1}{\sigma}} d\omega \right)^{\frac{\sigma}{\sigma-1}},$$

where C denotes aggregate consumption, Ω is the set of differentiated products available for purchase and $y(\omega)$ is the quantity of product ω used to produce the consumption good. Let the consumption good be the numeraire. Then cost minimization by producers of the consumption good implies that demand for each product is given by (1) and that the demand parameter satisfies $A = E$, where E denotes aggregate consumption expenditure. Market clearing requires $E = C$.

Creating the blueprint for a new differentiated product requires innovation. In order to innovate, a firm must hire a units of labor. a measures the cost of innovation. There is free entry into innovation and firms are risk neutral implying that in equilibrium:

$$aw \geq \pi_h, \tag{11}$$

where π_h denotes expected profits owning a blueprint. If the cost of innovation exceeds π_h, the inequality in (11) holds strictly and there is no innovation.

Innovation occurs at stage zero before the firm hires a supplier. In order to produce, an innovator must then establish a supply chain under incomplete contracts as described in Section 2. The supply chain technology parameters δ and γ are the same for all products. Since each firm faces the same demand elasticity σ, it follows that all firms have the same type of value chain. When characterizing the equilibrium I consider both the case where firms have inclusive value chains and the case where value chains are exclusive.

Suppose labor is homogeneous implying $w_h = w_m = w$. Headquarters firms and suppliers also face the same technology transfer costs meaning $f_h = f_m = f$. Technical change that reduces the cost of technology transfer within supply chains leads to a reduction in f.

Because the input production technology is imperfectly excludable suppliers face imitation risk. The imitation probability q is endogenous and depends upon how many firms seek to become imitators. There is free entry into imitation at stage three, but imitation is costly since it requires learning about a supplier's technology. Let M_m be the mass of input suppliers that are hired by headquarters firms and M_g be the mass of imitators. To become an imitator a firm must hire $b\mu$ units of labor, where b is an imitation cost parameter and $\mu = \mu\left(\frac{M_g}{M_m}\right)$ is an endogenous imitation cost that is higher when imitation targets are in relatively scarce supply.

Specifically, I assume $\mu(\cdot)$ is a differentiable, strictly increasing bijection from $[0,1)$ to $[0,\infty)$. This implies that the endogenous imitation cost is zero if there is no imitation, strictly increasing in the ratio of imitators M_g to imitation targets M_m, and becomes arbitrarily large as $M_g \to M_m$ from below. It follows that, whenever $M_m > 0$, equilibrium requires $0 < M_g < M_m$.

The imitation cost parameter b determines the excludability of the input production technology. A higher b implies the technology is harder to imitate. This could result from the production process being more difficult to reverse engineer, from workers lacking the skills required to reverse engineer technologies or from legal rules that increase imitation costs. For example, strengthening the intellectual property rights of input suppliers would increase b.

Each imitator is matched with a randomly chosen supplier and learns its input production technology. The matching technology is such that each input supplier matches with at most one imitator. Therefore, the free entry condition for imitation implies:

$$b\mu\left(\frac{M_g}{M_m}\right)w = \pi_g, \tag{12}$$

where π_g denotes the profits made by an imitator, which are given by substituting (7) into (4). In addition, the imitation risk faced by an input supplier is given by:

$$q = \frac{M_g}{M_m}. \tag{13}$$

This expression allows us to write μ as a function of q since $\mu\left(\frac{M_g}{M_m}\right) = \mu(q)$.

This completes the specification of the equilibrium value chain model. Since wages are the only source of income and the consumption good is the numeraire, both the real wage and consumption per capita equal w. It follows that wages are a sufficient statistic for welfare in this economy.

Before solving the model, I impose one additional assumption.

Assumption 1. *The following condition holds for all* $q \in [0,1)$*:*

$$\chi_1 \equiv \frac{(\tilde{\alpha}_h - \alpha_h)[\delta - \gamma(\sigma-1)] + (\tilde{\alpha}_m - \alpha_m)[\delta - (1-\gamma)(\sigma-1)]}{\hat{\alpha}_h[\delta - \gamma(\sigma-1)] + \hat{\alpha}_m[\delta - (1-\gamma)(\sigma-1)]} + \frac{\mu'(q)}{\mu(q)} > 0.$$

Assumption 1 is sufficient to ensure the existence of a unique equilibrium. As shown below, it guarantees that there is a unique imitation risk such that the free entry conditions for innovation and imitation hold simultaneously.

3.2 Equilibrium

In equilibrium the innovation and imitation free entry conditions hold with equality, expenditure equals income and the labor market clears. Aggregate profits net of entry costs are zero, meaning that wages are the only source of income and expenditure $E = wL$. Therefore, taking profits from (8), the innovation free entry condition (11) can be written as:

$$w = \left(\frac{\sigma-1}{\sigma}\right)^{\frac{\sigma}{\sigma-1}} \left(\frac{L}{\delta}\right)^{\frac{1}{\sigma-1}} \left[\frac{1}{\sigma-1}\frac{1}{a}\left(\hat{\alpha}_h[\delta-\gamma(\sigma-1)] + \hat{\alpha}_m[\delta-(1-\gamma)(\sigma-1)]\right)\right]^{\frac{\delta+1-\sigma}{\delta(\sigma-1)}} \times \left[\frac{1}{f}(\gamma\hat{\alpha}_h)^{\gamma}[(1-\gamma)\hat{\alpha}_m]^{1-\gamma}\right]^{\frac{1}{\delta}}. \tag{NE}$$

This expression gives the wage at which the cost of innovation equals expected profits. The wage depends upon the imitation risk q, but the sign of this effect depends upon whether the supply chain is inclusive or exclusive. Comparing (NE) with (8) shows that the wage is increasing in q in an inclusive value chain, but decreasing in q in an exclusive value chain. In an inclusive value chain higher imitation risk raises profits implying firms can afford to pay a higher wage. In an exclusive value chain the reverse is true. The wage is also decreasing in the innovation cost a and the technology transfer cost f since, all else equal, higher costs reduce profitability.

A successful imitator makes profits $\pi_g = \tilde{V}_g^*$ given by (4). Using (7) to substitute for the supplier's technology z and setting $E = wL$, free entry into imitation implies:

$$w = \left[\frac{1}{b\mu(q)} \frac{\tilde{\alpha}_m}{\sigma} \right]^{\frac{\delta+1-\sigma}{\delta(\sigma-1)}} \left[\left(\frac{\sigma-1}{\sigma} \right)^{1+\delta} \frac{L^{\frac{\delta}{\sigma-1}}}{\delta f} \left(\gamma \hat{\alpha}_h\right)^{\gamma} \left[(1-\gamma)\hat{\alpha}_m\right]^{1-\gamma} \right]^{\frac{1}{\delta}} . \tag{ME}$$

The imitation free entry condition (ME) gives the wage at which the imitation cost equals the expected profits of being an imitator as a function of imitation risk q. When imitation risk is very low, $\mu\left(q\right)$ is close to zero and the wage is unbounded above, while the wage tends to zero as q approaches one and $\mu\left(q\right)$ becomes arbitrarily large. Thus, an increase in imitation risk tends to reduce the wage w by making imitation more costly as the supply of imitation targets becomes relatively scarce. However, there is no guarantee that the relationship is monotonic for all values of q. Holding the imitation risk constant, an increase in the exogenous imitation cost b or the technology transfer cost f reduces profitability leading to a lower wage.

The equilibrium has a recursive structure. The innovation and imitation free entry conditions (NE) and (ME) are a pair of equations that determine the equilibrium wage w and imitation risk q. After solving these equations the labor market clearing conditions can be used to pin down the mass of innovators, suppliers and imitators. A solution to this system of equations exists and is unique.

Proposition 1. *When Assumption 1 holds, the value chains model has a unique equilibrium.*

A formal proof of Proposition 1 is given in Appendix A, but the properties of the equilibrium can be understood graphically. Figure 4 plots the innovation free entry condition (NE) and the imitation free entry condition (ME). Panel (a) shows the case where value chains are inclusive and the (NE) curve is upwards sloping in (q, w) space, while panel (b) shows the exclusive value chains case where it is downwards sloping. The slope of the (ME) curve is ambiguous, but the properties of $\mu\left(\cdot\right)$ and Assumption 1 ensure the two curves satisfy a single crossing property and that the (ME) curve cuts the (NE) curve from above. Consequently, there is a unique solution for q and w and the equilibrium is stable.[13]

The equilibrium depends upon three parameters that together determine the economy's technological development: the innovation cost a, the imitation cost b and the technology transfer cost f. Differentiating the equilibrium conditions (NE) and (ME) yields:

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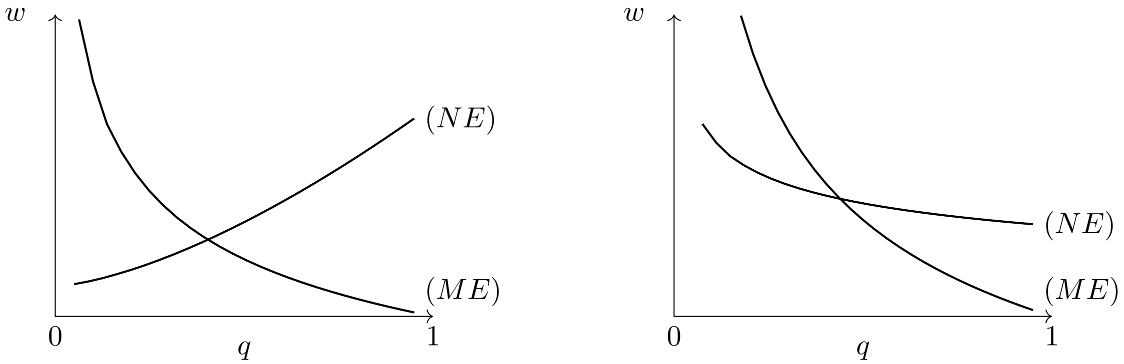
[13] The equilibrium is stable because if q exceeds its equilibrium value innovators can afford to pay a higher wage than imitators, which leads to a decline in q until equilibrium is restored. Conversely, if q is below its equilibrium value, imitators can afford higher wages than innovators leading to an increase in q.



(a) Inclusive value chains (b) Exclusive value chains

Figure 4: Closed economy equilibrium

$$
\begin{aligned}
dq &= \frac{1}{\chi_1}\left(\frac{da}{a} - \frac{db}{b}\right), \\
\frac{dw}{w} &= \frac{\delta + 1 - \sigma}{\delta(\sigma - 1)}\left(\frac{\chi}{\chi_1} - 1\right)\frac{da}{a} - \frac{\delta + 1 - \sigma}{\delta(\sigma - 1)}\frac{\chi}{\chi_1}\frac{db}{b} - \frac{1}{\delta}\frac{df}{f}.
\end{aligned}
\tag{14}
$$

Recall that χ_1 is positive by Assumption 1 and that χ is positive when value chains are inclusive and negative when value chains are exclusive.

Shocks that reduce the excludability of input technologies lead to a fall in b. Equation (14) shows that this leads to an increase in the equilibrium imitation risk as the number of imitators rises relative to the number of suppliers. However, the wage effect depends upon whether value chains are inclusive or exclusive. When b declines, the (ME) curve shifts illustrated by the shift from the solid line to the dashed line in Figure 5. With inclusive value chains this shifts the equilibrium up the (NE) curve, as shown in panel (a), and wages increase. By contrast, when value chains are exclusive, the (NE) curve is downwards sloping, as shown in panel (b), and a reduction in b leads to lower wages.

When the economy becomes better at innovation, a declines leading to a reduction in imitation risk as the number of innovators that set-up supply chains rises relative to the number of imitators. When value chains are exclusive this necessarily leads to higher wages, whereas in an inclusive value chains economy the wage effect is ambiguous.[14]

Finally, inspection of (14) shows that when the cost of technology transfer declines imitation risk is unaffected and wages increase. Similarly, balanced technical change that reduces the innovation cost and the imitation cost by the same proportion raises wages (for all types of value chains), while leaving imitation

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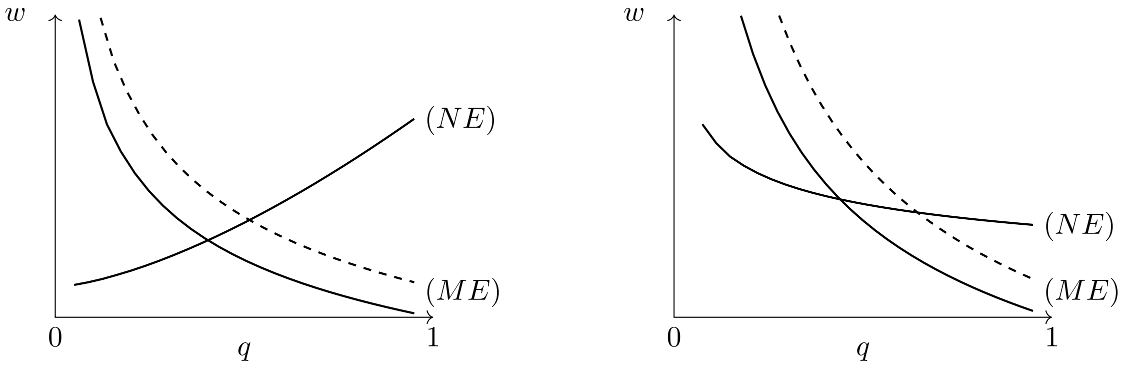
[14] The sign of the wage effect depends upon the slope of the (ME) curve. If this slope is positive at the equilibrium, then a marginal reduction in a reduces the equilibrium wage.



(a) Inclusive value chains: wages increase

(b) Exclusive value chains: wages fall

Figure 5: Reduction in imitation costs

risk unchanged. Proposition 2 summarizes these results.

Proposition 2. *Suppose Assumption 1 holds. Then:*

(i) A reduction in the imitation cost b increases imitation risk, raises real wages when value chains are inclusive and reduces real wages when value chains are exclusive;

(ii) A reduction in the innovation cost a reduces imitation risk and raises real wages when value chains are exclusive;

(iii) Either balanced technical change that reduces the innovation cost and the imitation cost by the same proportion, or a reduction in the cost of technology transfer f, does not affect imitation risk and raises real wages.

As economies develop, their technological possibilities expand and their institutions and laws evolve. In the model, these changes affect the innovation cost a, the imitation cost b and the technology transfer cost f. Proposition 2 shows that the effect of these parameters on wages and imitation risk depends upon the bias of technological and institutional change and, in some circumstances, the nature of value chains. Balanced development that reduces entry and technology transfer costs is unambiguously welfare enhancing. However, a shock that only lowers imitation costs, such as a weakening in intellectual property protection for input technologies, reduces welfare when value chains are exclusive.

4 Offshoring Model

This section builds upon the general equilibrium model developed above to study offshoring in an environment where contracts are incomplete and technology diffusion occurs within supply chains. The model features two countries: an innovative, high wage Northern economy, and; a low wage Southern economy that is a potential destination for supply chain offshoring. I use the open economy model to analyze how offshoring affects production, productivity, wages and welfare.

4.1 Open Economy Set-up

There are two countries: North N and South S, which I denote using $j = N, S$ superscripts. The structure of preferences and production possibilities is the same as in the closed economy. However, countries differ in terms of their innovation cost a^j, imitation cost b^j, technology transfer cost f^j and population L^j. In keeping with the product cycle literature, I assume a^S is sufficiently large that the South does not innovate in equilibrium. I also assume L^N is sufficiently large relative to L^S that, in equilibrium, headquarters firms hire suppliers in both countries.

The consumption good is non-tradable, but there is free trade in inputs and differentiated products implying that prices do not vary across countries. Let the consumption good be the numeraire. Cost minimization by consumption good producers then implies the demand parameter A equals global consumption expenditure E and market clearing requires $E = C^N + C^S$.

As there is no innovation in the South, all headquarters firms are based in the North and pay wages w^N to their knowledge transfer workers. Headquarters firms can choose whether to hire a supplier in the North or the South. If the supplier is located in country j then $w_m = w^j$. Wages are again the only source of income in the open economy, implying that w^j equals both the real wage and consumption per capita in country j and that cross-country income and welfare differences are determined by relative wages.

Technology transfer costs not only vary across countries, but also depend upon whether supply chains are domestic or international. For a domestic supply chain located in the North $f_h = f_m = f^N$. However, if the firm hires a foreign supplier it must pay an additional cost of international technology transfer meaning $f_h = \lambda f^N$ and $f_m = \lambda f^S$ where $\lambda > 1$. Technical change that facilitates offshoring by reducing international technology transfer costs, for example an improvement in communications, leads to a decline in λ.

As in the closed economy, there is free entry into imitation at stage three. Consistent with evidence that international knowledge flows are much weaker than domestic flows (Jaffe, Trajtenberg and Henderson 1993; Branstetter 2001; Keller 2002), I assume all imitation occurs within countries. Consequently, the imitation probability q^j varies by country j and the endogenous imitation cost is given by $\mu^j = \mu\left(\frac{M_g^j}{M_m^j}\right) = \mu\left(q^j\right)$. Because imitation risk is country-specific, the expected payoff coefficients $\hat{\alpha}_h$ and $\hat{\alpha}_m$ defined in (6) depend upon whether the headquarters firm hires a supplier in the North or the South. When the supplier is in country j, the expected payoff coefficients are $\hat{\alpha}_i^j = \alpha_i + q^j\left(\tilde{\alpha}_i - \alpha_i\right)$ for $i = h, m$.

Finally, I assume that both Assumption 1 and the following assumption hold.

Assumption 2. *The following condition holds for all* $q \in [0,1)$*:*

$$\begin{aligned}\chi_2 \equiv\ & \frac{\left(\tilde{\alpha}_h - \alpha_h\right)\left[\delta - \gamma\left(\sigma - 1\right)\right] + \left(\tilde{\alpha}_m - \alpha_m\right)\left[\delta - \left(1 - \gamma\right)\left(\sigma - 1\right)\right]}{\hat{\alpha}_h\left[\delta - \gamma\left(\sigma - 1\right)\right] + \hat{\alpha}_m\left[\delta - \left(1 - \gamma\right)\left(\sigma - 1\right)\right]} \\ & + \frac{\sigma - 1}{\delta\sigma - \gamma(\sigma - 1)}\left[\frac{\gamma\left(\tilde{\alpha}_h - \alpha_h\right)}{\hat{\alpha}_h} + \frac{\left(1 - \gamma\right)\left(\tilde{\alpha}_m - \alpha_m\right)}{\hat{\alpha}_m} + \left(\delta + 1 - \gamma\right)\frac{\mu'\left(q\right)}{\mu\left(q\right)}\right] > 0.\end{aligned}$$

Assumption 1 implies that the Northern equilibrium conditions satisfy a single crossing property and Assumption 2 has analogous implications for the South. Both Assumptions 1 and 2 impose lower bounds on the elasticity of the imitation cost function $\mu\left(\cdot\right)$, but it is ambiguous which bound is tighter.

4.2 Offshoring Equilibrium

Headquarters firms may establish supply chains in either the North or the South. For firms to hire suppliers in both countries it must be that they are indifferent between using Northern and Southern suppliers. Using (8) to obtain the expected profits from hiring a supplier in each country, indifference requires:

$$\frac{w^S}{w^N} = \left[\left(\frac{\hat{\alpha}_h^S\left[\delta - \gamma\left(\sigma - 1\right)\right] + \hat{\alpha}_m^S\left[\delta - \left(1 - \gamma\right)\left(\sigma - 1\right)\right]}{\hat{\alpha}_h^N\left[\delta - \gamma\left(\sigma - 1\right)\right] + \hat{\alpha}_m^N\left[\delta - \left(1 - \gamma\right)\left(\sigma - 1\right)\right]}\right)^{\frac{\delta + 1 - \sigma}{\sigma - 1}} \frac{1}{\lambda}\left(\frac{\hat{\alpha}_h^S}{\hat{\alpha}_h^N}\right)^{\gamma}\left(\frac{\hat{\alpha}_m^S}{\hat{\alpha}_m^N}\frac{f^N}{f^S}\right)^{1 - \gamma}\right]^{\frac{1}{\delta + 1 - \gamma}}. \tag{OS}$$

The offshoring indifference condition (OS) gives the Southern relative wage w^S/w^N at which headquarters firms are indifferent over supplier location. The relative wage is decreasing in f^S/f^N (provided $\gamma < 1$) and in λ, since a decline in either of these parameters reduces the relative cost of technology transfer to the South. However, these are partial equilibrium relationships. The relative wage also depends upon the endogenous imitation probabilities q^S and q^N through the expected payoff coefficients $\hat{\alpha}_i^j$ for $i = h, m$ and $j = N, S$. The effect of imitation risk on the value of offshoring depends upon whether the supply chain is inclusive or exclusive. Comparing (OS) with (8) shows that in an inclusive supply chain the Southern relative wage is increasing in q^S and decreasing in q^N. By contrast, in an exclusive supply chain these relationships are reversed.

In addition to the (OS) condition, equilibrium requires that the innovation free entry condition (11) holds with equality in the North, that the imitation free entry condition (12) holds with equality in both countries and that markets clear. Appendix A gives the equilibrium conditions and proves that there exists a unique equilibrium.

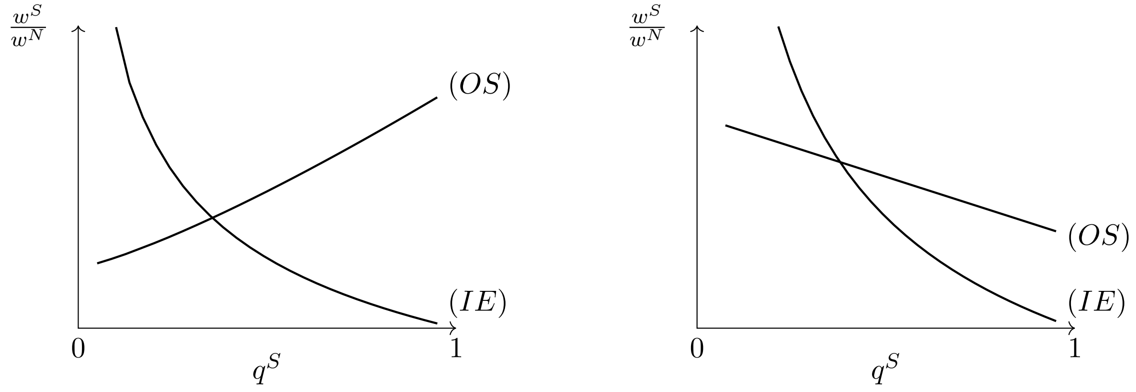
Proposition 3. *When Assumptions 1 and 2 hold, the offshoring model has a unique equilibrium.*

In the North, the equilibrium conditions are similar to those for the closed economy in Section 3.2. In particular, the equilibrium imitation risk q^N is unaffected by offshoring. This invariance property of the equilibrium is a consequence of the assumption that the North is sufficiently large relative to the South that firms hire suppliers in both countries. When this assumption holds, the Northern wage w^N depends upon offshoring only through changes in global consumption expenditure E. An increase in expenditure raises w^N due to increased demand for Northern output. It follows immediately that Northern wages are higher in the offshoring equilibrium than in autarky because of the additional demand coming from Southern consumers.

Offshoring also raises wages in the South due to the increased demand for Southern labor from suppliers and imitators producing inputs for Northern firms. To characterize equilibrium in the South, note that when the imitation free entry condition (12) holds in both countries:

$$\frac{w^S}{w^N} = \left[\left(\frac{b^N \mu\left(q^N\right)}{b^S \mu\left(q^S\right)} \right)^{\frac{\delta+1-\sigma}{\sigma-1}} \frac{1}{\lambda} \left(\frac{\hat{\alpha}_h^S}{\hat{\alpha}_h^N} \right)^{\gamma} \left(\frac{\hat{\alpha}_m^S}{\hat{\alpha}_m^N} \frac{f^N}{f^S} \right)^{1-\gamma} \right]^{\frac{\sigma-1}{\delta\sigma-\gamma(\sigma-1)}} . \tag{IE}$$

Conditional on q^N, the offshoring indifference condition (OS) and the imitation entry condition (IE) give a pair of equations in w^S/w^N and q^S. The properties of these equations are analogous to those of the (NE) and (ME) conditions in the closed economy, as shown in Figure 6. The (OS) curve is upwards sloping when supply chains are inclusive (panel a) and downwards sloping when supply chains are exclusive (panel b). The slope of the (IE) curve is ambiguous, but Assumption 2 ensures the two curves always satisfy a single crossing property and that the (IE) curve cuts the (OS) curve from above. The intersection determines the equilibrium values of w^S/w^N and q^S.



(a) Inclusive value chains

(b) Exclusive value chains

Figure 6: Open economy equilibrium

How do shocks to the Southern economy affect equilibrium wages and the imitation probability in the South? Southern development may result in either a decline in the imitation cost b^S, or a decline in the technology transfer cost f^S.[15] Legal and institutional changes in the South that affect the excludability of input technologies will also affect b^S. And technical change that reduces the cost of international technology transfer will lead to a reduction in λ. Taking the total derivatives of (OS) and (IE) with respect to these parameters yields:

$$\begin{aligned} dq^S &= \frac{1}{\chi_2}\frac{\sigma-1}{\delta\sigma-\gamma(\sigma-1)}\left[-(\delta+1-\gamma)\frac{db^S}{b^S}+(1-\gamma)\frac{df^S}{f^S}+\frac{d\lambda}{\lambda}\right], \\ \frac{d\left(w^S/w^N\right)}{w^S/w^N} &= -\frac{\delta+1-\sigma}{\delta\sigma-\gamma(\sigma-1)}\frac{\chi}{\chi_2}\frac{db^S}{b^S}+\frac{1}{\delta+1-\gamma}\left(\frac{\delta+1-\sigma}{\delta\sigma-\gamma(\sigma-1)}\frac{\chi}{\chi_2}-1\right)\left[(1-\gamma)\frac{df^S}{f^S}+\frac{d\lambda}{\lambda}\right]. \end{aligned} \tag{15}$$

Consider, first, the consequences of a decline in b^S. The value of b^S does not affect imitation risk in the North q^N. Therefore, the offshoring indifference condition (OS) is independent of b^S. However, a reduction in b^S shifts the imitation entry curve (IE) outwards because, for a given imitation probability q^S, Southern imitators can afford to pay higher wages when entry is less costly. Equation (15) shows that this leads to an increase in the equilibrium imitation risk q^S. However, the sign of the relative wage effect depends upon the nature of supply chains. With inclusive supply chains $\chi > 0$ and an increase in Southern imitation risk

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[15] As the South develops, its innovation cost a^S will also decline. However, provided a^S remains too high for innovation to be profitable in the South, the offshoring equilibrium is independent of a^S.

makes setting up a supply chain in the South more attractive, which leads to an increase in the Southern relative wage w^S/w^N. But with exclusive supply chains, the reverse happens and the Southern relative wage declines. Thus, the effect of a reduction in the cost of imitation in the South is qualitatively different in inclusive and exclusive supply chains.

A higher Southern relative wage increases global demand E for a given Northern wage and, in equilibrium, higher demand leads to an increase in w^N. It follows that when supply chains are inclusive both w^S and w^N increase when the imitation cost b^S declines, whereas under exclusive supply chains wages fall in both countries. Consequently, with exclusive supply chains, development that reduces Southern imitation costs is globally immiserizing. In contrast to Bhagwati (1958), development is immiserizing not because of changes in the terms of trade, but because higher imitation risk exacerbates the inefficiencies due to incomplete contracts leaving both countries worse off.

An immediate corollary of these comparative statics is that when supply chains are inclusive, optimal intellectual property policy in the South is to minimize the legal excludability of suppliers' input technologies. Whereas, with exclusive supply chains, the reverse is true and optimal policy is to provide as much intellectual property protection as possible to suppliers. In both cases, the policy preferences of workers in the South, workers in the North and headquarters firms that are yet to set-up a supply chain are aligned. However, recall from Section 2.5 that after technology transfer has occurred at stage two, headquarters firms prefer higher imitation risk, while suppliers prefer lower imitation risk. Consequently, changes in intellectual property policy that occur after stage two, but before imitation occurs at stage three, will generate conflict between headquarters firms and suppliers.

A decline in either f^S or λ reduces the cost of technology transfer to the South. This makes the South a more attractive location for offshoring and, consequently, the relative wage in the South rises, as do the wage levels in both the South and the North, regardless of whether supply chains are inclusive or exclusive.[16] The increase in Southern wages is sufficient to make imitation less attractive and imitation risk q^S falls. Proposition 4 summarizes these result.

Proposition 4. *Suppose Assumptions 1 and 2 hold. Then:*

(i) A decline in the Southern imitation cost b^S increases imitation risk in the South, does not affect imitation risk in the North and: (a) when supply chains are inclusive, increases real wages in both countries and the

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[16] This follows from equation (15) after observing that $(\delta + 1 - \sigma)\chi < [\delta\sigma - \gamma(\sigma - 1)]\,\chi_2$. See the proof of Proposition 4 for details.

relative wage in the South; (b) when supply chains are exclusive, decreases real wages in both countries and the relative wage in the South.

(ii) A decline in the Southern technology transfer cost f^S in any economy where the knowledge transfer share $\gamma < 1$, or a decline in the international technology transfer cost λ: reduces imitation risk in the South, does not affect imitation risk in the North, raises the relative wage in the South and increases real wages in both countries.

Proposition 4 characterizes the effects of shocks that affect production in the South, but not the North. We can also analyze the consequences of global technical change. Suppose all innovation and imitation costs fall by the same proportion. Inspection of the equilibrium conditions shows that the imitation risks $q^j, j = N, S$ and the Southern relative wage are unaffected, while wages in both countries increase. The same holds following a decline in technology transfer costs that leaves f^N/f^S unaffected.

Proposition 5. *Suppose Assumptions 1 and 2 hold. Balanced global technical change that reduces all innovation and imitation costs by the same proportion, or that reduces Northern and Southern technology transfer costs by the same proportion, leads to an increase in the real wage in both countries, but does not affect the imitation risk in either country or relative wage levels.*

Proposition 5 shows that balanced global technical change is always welfare enhancing for both countries. Whether supply chains are inclusive or exclusive does not matter in the event of balanced technical change because imitation risk is unaffected in both countries, meaning that the slope of the (OS) curve is immaterial.

4.3 Supply Chain Choice

The analysis above considers both the case where supply chains are exclusive and the case where supply chains are inclusive. But it does not allow for the co-existence of different types of supply chains. Supply chain homogeneity is a consequence of the assumption that all supply chains have the same knowledge transfer share γ and elasticity of technology transfer costs δ, and that all firms face the same demand elasticity σ.

Suppose instead that when a headquarters firm establishes its supply chain it chooses between two alternative types of supply chain: an inclusive supply chain or an exclusive supply chain. The firm's choice determines the knowledge transfer share γ and the elasticity of technology transfer costs δ in its supply chain. The inclusive supply chain has knowledge transfer share γ_i and elasticity of technology transfer costs

δ_i, while the exclusive supply chain has parameters γ_e and δ_e. Neither the cost of innovation nor the demand elasticity the firm faces depend upon what type of supply chain the innovator chooses.

Supply chain type is observable and each imitator can target either inclusive or exclusive supply chains. The imitation cost b^j is the same in either case, but the endogenous imitation cost $\mu(\cdot)$ depends upon the ratio of imitators to suppliers by supply chain type. Let M^j_{gk} denote the mass of imitators that target type $k = i, e$ supply chains in country $j = N, S$ and M^j_{mk} denote the mass of suppliers using type k supply chains. Then the endogenous imitation cost for imitators targeting type k supply chains in country j is $\mu\left(\frac{M^j_{gi}}{M^j_{mi}}\right)$. It follows that when headquarters firms operate both types of supply chains in the same country, imitation risk will vary by supply chain type. In all other respects, the model is as described in Section 4.1 and Assumptions 1 and 2 hold with $\gamma = \gamma_k$ and $\delta = \delta_k$ for $k = i$ and $k = e$.

How do Southern imitation costs b^S affect whether headquarters firms that offshore to the South operate inclusive or exclusive supply chains? As in the baseline model, all else constant, a decline in b^S raises the expected profits from offshoring using an inclusive supply chain and reduces the expected profits from offshoring using an exclusive supply chain. Supposing that neither supply chain type dominates the other for all $b^S > 0$, it follows that there exists a threshold imitation cost b^{S*} such that offshorers use exclusive supply chains when $b^S \geq b^{S*}$ and inclusive supply chains when $b^S \leq b^{S*}$.

Likewise, there exists a threshold b^{N*} such that firms that hire Northern suppliers use exclusive supply chains if and only if $b^N \geq b^{N*}$. The Northern threshold is independent of the parameters of the Southern economy, but shocks to the Northern economy do affect b^{S*}. Proposition 6 summarizes equilibrium supply chain choice.

Proposition 6. *Suppose Assumptions 1 and 2 hold and that innovators can choose between operating inclusive or exclusive supply chains. In each country $j = N, S$ there exists a threshold b^{j*} such that, in equilibrium, input production in j uses inclusive supply chains if and only if the imitation cost b^j is below the threshold.*

Proposition 6 has several interesting implications. First, countries with high imitation costs tend to use exclusive supply chains, whereas those with low imitation costs tend to use inclusive supply chains. Thus, technological development and the strength of intellectual property rights affect how countries sort across supply chain types. Second, firms that offshore may use a different type of supply chain from firms that hire domestic suppliers. However, except in knife-edge cases, there is no heterogeneity in the type of supply chain used within a country.

Third, the relative Southern wage w^S/w^N is U-shaped as a function of imitation costs b^S as shown in Figure 7. When imitation costs are above the threshold b^{S*}, a decline in b^S leads to a fall in the relative wage because the South uses exclusive supply chains and, as b^S falls, imitation risk rises and Southern supply chains become less profitable. However, if b^S continues to decline until it crosses the threshold, offshorers switch to using inclusive supply chains meaning that lower imitation costs increase the relative Southern wage. The same reasoning implies that real wages in both countries are U-shaped as a function of b^S.

A corollary of this observation is that policy makers have an incentive to set intellectual property policy to polarize imitation costs. For a marginal change in intellectual property protection of input technologies to be welfare enhancing it should tighten protection and increase b^S when imitation costs are above the threshold b^{S*}, but loosen protection when imitation costs are below the threshold. Since changes in b^S move w^S and w^N in the same direction, there is no international dispute over optimal Southern intellectual property policy. However, it may be optimal for Southern intellectual property policy to diverge from Northern policy.

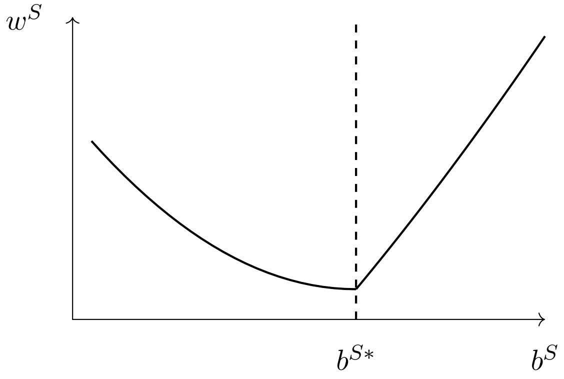

Figure 7: Imitation costs and wages with supply chain choice

5 Knowledge Spillovers

The effect of reductions in imitation costs on wages depends upon whether value chains are inclusive or exclusive. However, for both types of value chain, social preferences over imitation costs are aligned with the private (ex-ante) preferences of headquarters firms. To see why, consider a closed economy and impose one additional assumption.

Assumption 3. *The following condition holds for all* $q \in [0,1)$*:*

$$\chi_3 \equiv \frac{\sigma-1}{\delta+1-\sigma}\left[\frac{\gamma\left(\tilde{\alpha}_h-\alpha_h\right)}{\hat{\alpha}_h}+\frac{\left(1-\gamma\right)\left(\tilde{\alpha}_m-\alpha_m\right)}{\hat{\alpha}_m}\right]-\frac{\mu'\left(q\right)}{\mu\left(q\right)}<0.$$

Assumption 3 implies that the (ME) curve is strictly downwards sloping for all values of q. Now suppose that at the innovation stage, firms can choose between two ways of doing research. *Open research* where the firm shares the process knowledge it learns from its innovative efforts, while maintaining ownership of the product blueprint it creates. And *secret research* where the firm hoards any knowledge it creates. The firm's choice does not affect its innovation cost a, but the imitation cost b is lower when imitators target suppliers of firms that undertake open research.

When value chains are inclusive, innovators opt for open research because they anticipate that a reduction in the imitation cost leads to higher imitation risk and, consequently, higher expected profits from innovation. But because there is free entry into innovation, the equilibrium effect of innovators choosing open research is to increase wages and welfare as shown in Proposition 2. Thus, innovators' private choices are socially efficient. When value chains are exclusive, innovators undertake secret research, but, once again, this choice is socially efficient because it leads to higher wages. It follows that in an economy where imitation costs depend upon whether innovators share or conceal knowledge, innovators' private incentives deliver the efficient outcome regardless of supply chain type.[17]

However, the alignment of private and social incentives is not guaranteed in economies with knowledge spillovers. When headquarters firms' choices affect knowledge spillovers to the broader economy, exclusive value chains can lead to conflict between private incentives and social efficiency. The misalignment arises because headquarters firms' desire to lower imitation risk by reducing knowledge diffusion does not account for the social benefits of knowledge spillovers. This tension does not arise in inclusive value chains, where headquarters firms have an incentive to share knowledge and promote knowledge spillovers.

To formalize this intuition, suppose the imitation cost is b for secret research and $\left(1-\zeta^b\right)b$ for open research with $0<\zeta^b<1$. The larger is ζ^b, the more open research reduces imitation costs. In addition, suppose that open research generates knowledge spillovers that reduce innovation costs for other firms. Let the innovation cost be $\left(1-\zeta^a x\right)a$ where x denotes the fraction of innovators that choose open research and

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[17] The proof of Proposition 7 provides a formal analysis of how innovators choose between open and secret research.

$0 < \zeta^a < 1$. This specification introduces knowledge spillovers into the technology transfer model developed above and makes the extent of spillovers dependent upon the actions of headquarters firms. It captures the idea that, in addition to reducing the cost of imitation, sharing research findings prevents wasteful duplication of research leading to lower innovation costs. For simplicity, I assume there are no scale effects in knowledge spillovers by letting x depend upon the share of innovators that perform open research.

Innovators take the cost of innovation as exogenous, but internalise how their actions affect the cost of imitating their supplier. It follows that the introduction of knowledge spillovers does not affect the incentive to undertake open research. When value chains are exclusive all innovators choose secret research and $x = 0$, whereas when value chains are inclusive all innovators perform open research and $x = 1$. Conditional on these choices, the equilibrium is as described in Section 3.2. Since Assumption 3 guarantees the (ME) curve is downwards sloping, open research is socially optimal if value chains are inclusive because reductions in imitation and innovation costs both raise wages (see equation 14).

But when value chains are exclusive, secret research need not be socially optimal. Although a higher imitation cost is wage increasing, a higher innovation cost is wage reducing. The relative strengths of the two effects depends upon ζ^a and ζ^b, but the impact of weaker knowledge spillovers can dominate the reduction in imitation costs. Suppose, for example, $\zeta^a = \zeta^b$ implying open research leads to balanced technical change that reduces innovation and imitation costs by the same proportion. Part (iii) of Proposition 2 shows that balanced technical change raises wages in both inclusive and exclusive value chains. It follows that, in this case, headquarters firms' private incentive to conceal knowledge is welfare reducing. Proposition 7 summarizes this result.

Proposition 7. *Consider a closed economy where Assumptions 1 and 3 hold. Suppose that innovators can choose between open research and secret research, where open research reduces imitation costs and may also generate knowledge spillovers that reduce innovation costs. Then innovators choose open research when value chains are inclusive and secret research when value chains are exclusive and:*
(i) In the absence of knowledge spillovers, innovators make socially optimal research type choices in both inclusive and exclusive supply chains;
(ii) When there are knowledge spillovers, innovators make socially optimal research type choices in inclusive supply chains, but their choices may be welfare reducing in exclusive value chains.

A dynamic analysis of the growth consequences of supply chain type lies beyond the scope of this paper. Nevertheless, Proposition 7 identifies a novel mechanism through which development dynamics may differ depending upon whether countries belong to inclusive or exclusive supply chains. In inclusive supply chains, a sharing incentive promotes the diffusion of knowledge beyond the headquarters-supplier relationship. By contrast, when supply chains are exclusive innovators' desire to prevent supplier imitation may limit knowledge diffusion outside value chains resulting in a less productive and poorer economy.

6 Conclusions

Supply chain relationships create new channels for technology diffusion. When diffusion occurs through product imitation, the interests of product owners and imitators necessarily conflict. But when production takes place within global value chains, diffusion may be mutually beneficial for product owners and their suppliers.

Although an extensive empirical literature documents the existence of vertical technology transfers, there has been little theoretical analysis of either the mechanisms that determine technology transfer incentives within supply chains, or the general equilibrium consequences of diffusion through supply chains. To address these questions, this paper develops a theory of technology transfer in value chains that allows for incomplete contracts and imperfectly excludable input production technologies. Incomplete contracts lead to a hold-up problem that causes inefficiently low investment in technology transfer and input production, while supplier imitation affects the division of value chain surplus.

The theory shows that the role of value chains in technology diffusion depends upon the scope of headquarters firms' sharing incentive. In inclusive value chains, headquarters firm benefit from supplier imitation and have an incentive to encourage technology diffusion beyond the supply chain. Whereas, in exclusive value chains, the headquarters firm seeks to prevent diffusion. Embedding the technology transfer model in general equilibrium shows that the distinction between inclusive and exclusive value chains is important for optimal intellectual property policy and the welfare consequences of changes in innovation and imitation costs. Technical change that is welfare increasing in an economy with inclusive value chains, can be welfare decreasing when value chains are exclusive.

To highlight the novel mechanisms that arise when technology transfer occurs within global value chains, this paper has used a relatively simple supply chain framework. In future work the model could be extended to incorporate other important features of value chains such as partial input contractibility, multiple stages of production and the choice between integration and outsourcing. It would also be interesting to analyze technology transfer incentives when some inputs are homogeneous and to develop a dynamic version of the model to study how the presence or absence of sharing incentives affects growth in inclusive and exclusive value chains. From an empirical perspective, the paper offers a rich set of testable predictions on firm-level behavior within supply chains and poses the challenge of how to construct measures of supply chain type.

Understanding the relationship between supply chains and technology diffusion is also important for industrial policy. Although global value chains create new opportunities for developing economies to industrialize and catch-up with richer countries, not all value chains are created equal. To maximize the benefits of value chain participation, countries need to tailor their investment incentives and intellectual property rights to fit their role in global supply chains. This paper provides a conceptual framework for evaluating supply chain policy.

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Appendices

A Proofs and derivations

Proof of Proposition 1

The proof has two parts. First, I show that the pair of equations (NE) and (ME) give a unique solution for w and q. Then I use the labor market clearing conditions to solve for the mass of headquarters firms, suppliers and imitators.

Figure 4 plots equations (NE) and (ME) in (q, w) space. The properties of $\mu(\cdot)$ ensure that the (ME) curve lies above the (NE) curve for q sufficiently close to zero, but below it for q sufficiently close to one. Since both curves are continuous in q, the existence of an equilibrium is guaranteed.

Next, taking the total derivative of (NE) gives:

$$\begin{aligned}\frac{dw}{w} &= \frac{\delta+1-\sigma}{\delta(\sigma-1)}\left[\frac{(\tilde{\alpha}_h-\alpha_h)\left[\delta-\gamma(\sigma-1)\right]+(\tilde{\alpha}_m-\alpha_m)\left[\delta-(1-\gamma)(\sigma-1)\right]}{\hat{\alpha}_h\left[\delta-\gamma(\sigma-1)\right]+\hat{\alpha}_m\left[\delta-(1-\gamma)(\sigma-1)\right]}dq-\frac{da}{a}\right] \\ &\quad+\frac{1}{\delta}\left[\frac{\gamma(\tilde{\alpha}_h-\alpha_h)}{\hat{\alpha}_h}dq+\frac{(1-\gamma)(\tilde{\alpha}_m-\alpha_m)}{\hat{\alpha}_m}dq-\frac{df}{f}\right],\end{aligned} \tag{16}$$

while the derivative of (ME) is:

$$\frac{dw}{w}=\frac{\delta+1-\sigma}{\delta(\sigma-1)}\left[-\frac{db}{b}-\frac{\mu'(q)}{\mu(q)}dq\right]+\frac{1}{\delta}\left[\frac{\gamma(\tilde{\alpha}_h-\alpha_h)}{\hat{\alpha_h}}dq+\frac{(1-\gamma)(\tilde{\alpha}_m-\alpha_m)}{\hat{\alpha_m}}dq-\frac{df}{f}\right]. \tag{17}$$

Setting $da = db = df = 0$ and comparing these expressions shows that when Assumption 1 holds the (ME) curve must cross the (NE) curve from above. It follows that the two curves have a single crossing and their intersection determines the equilibrium values of w and q.

Now consider labor market clearing. A headquarters firm employs a innovation workers and $f\left(z_h\right)^{\delta}$ knowledge transfer workers, where z_h is given by (5) with $A = wL$, $w_m = w_h = w$ and $f_m = f_h = f$. Therefore, its total employment is $l_h = a + f\left(z_h\right)^{\delta}$.

Supplier employment depends upon whether or not imitation occurs. Employment at the average supplier is given by:

$$\mathbb{E}l_m = f\left(z_m\right)^{\delta} + \frac{(1-q)y_m + q\tilde{y}_m}{z},$$

where z_m is given by (5), y_m and $\tilde{y}_m$ are given by (3) and z is the supplier's equilibrium technology given by (7) with $A = wL$, $w_m = w_h = w$ and $f_m = f_h = f$. Imitators hire workers to undertake imitation and to produce inputs. Therefore, each imitator has employment $l_g = b\mu(q) + \tilde{y}_m/z$.

Crucially, the expressions above imply that employment at all headquarters firms, suppliers and imitators is uniquely determined by the equilibrium values of w and q. All that remains is to solve for the equilibrium mass of headquarters firms M_h, suppliers M_m and imitators M_g. Labor market clearing requires:

$$L = M_h l_h + M_m \mathbb{E}l_m + M_g l_g.$$

Since all headquarters firms hire one supplier we must have that $M_h = M_m$ and equation (13) gives $M_g = qM_m$. Together with the labor market clearing condition, these two equations form a system of three linear equations in the three unknowns M_h, M_m and M_g. Solving this system implies that the mass of headquarters firms is given by:

$$M_h = \frac{L}{l_h + \mathbb{E}l_m + ql_g}.$$

This completes the proof of Proposition 1.

Proof of Proposition 2

The only comparative static that does not follow immediately from equation (14) is how variation in a affects wages. This relationship is positive if and only if $\chi > \chi_1$. Assumption 1 implies $\chi_1 > 0$. Therefore, when supply chains are exclusive and $\chi < 0$ it must be that a reduction in a increases wages. By contrast, when supply chains are inclusive and $\chi > 0$ the relative size of χ and χ_1 is ambiguous.

Proof of Proposition 3

The proof has three parts. First, I write down the equilibrium conditions and show that the equilibrium has a recursive structure. Second, I prove that there exists a unique solution for w^S, w^N, q^S, q^N and E. Finally, I use the labor market clearing conditions to solve for the remaining equilibrium variables.

Taking profits from (8), the innovation free entry condition in the North (11) is:

$$w^N = \left[\frac{1}{\sigma-1}\frac{1}{a^N}\left(\hat{\alpha}_h^N\left[\delta-\gamma\left(\sigma-1\right)\right]+\hat{\alpha}_m^N\left[\delta-\left(1-\gamma\right)\left(\sigma-1\right)\right]\right)\right]^{\frac{\delta+1-\sigma}{\delta\sigma}} \\ \times\frac{\sigma-1}{\sigma}\left(\frac{E}{\delta}\right)^{\frac{1}{\sigma}}\left[\frac{1}{f^N}\left(\gamma\hat{\alpha}_h^N\right)^{\gamma}\left[(1-\gamma)\hat{\alpha}_m^N\right]^{1-\gamma}\right]^{\frac{\sigma-1}{\delta\sigma}}. \tag{18}$$

This expression gives the Northern wage as a function of global consumption expenditure E and the Northern imitation probability q^N.

A successful imitator makes profits $\pi_g^j = \tilde{V}_g^{j*}$ given by (4). Using (7) to substitute for the supplier's technology z, free entry into imitation in the North implies:

$$w^N = \left[\frac{1}{b^N\mu(q^N)}\frac{\tilde{\alpha}_m}{\sigma}\right]^{\frac{\delta+1-\sigma}{\delta\sigma}}\left[\left(\frac{\sigma-1}{\sigma}\right)^{1+\delta}\frac{E^{\frac{\delta}{\sigma-1}}}{\delta f^N}\left(\gamma\hat{\alpha}_h^N\right)^{\gamma}\left[(1-\gamma)\hat{\alpha}_m^N\right]^{1-\gamma}\right]^{\frac{\sigma-1}{\delta\sigma}}, \tag{19}$$

while free entry into imitation in the South requires:

$$w^S = \left(\frac{w^S}{w^N}\right)^{\frac{\gamma(\sigma-1)}{\delta\sigma}}\left[\frac{1}{b^S\mu(q^S)}\frac{\tilde{\alpha}_m}{\sigma}\right]^{\frac{\delta+1-\sigma}{\delta\sigma}}\left[\left(\frac{\sigma-1}{\sigma}\right)^{1+\delta}\frac{E^{\frac{\delta}{\sigma-1}}}{\delta\lambda}\left(\frac{\gamma\hat{\alpha}_h^S}{f^N}\right)^{\gamma}\left(\frac{(1-\gamma)\hat{\alpha}_m^s}{f^S}\right)^{1-\gamma}\right]^{\frac{\sigma-1}{\delta\sigma}}. \tag{20}$$

The imitation free entry conditions express the wage in each country w^j as a function of global consumption expenditure E and the imitation risk in that country q^j. Dividing equation (20) by equation (19) yields the (IE) condition given in Section 4.2.

Equilibrium also requires that global expenditure equals total factor income:

$$E = w^S L^S + w^N L^N, \tag{21}$$

and that the labor market clears in both countries. The equilibrium has a recursive structure. The offshoring indifference condition (OS) together with equations (18)-(21) comprise five equations in the five variables w^S, w^N, q^S, q^N and E. After solving these equations the labor market clearing conditions can be used to pin down the mass of innovators, suppliers and imitators in each country.

Combining the innovation and imitation free entry conditions in the North yields:

$$1 = \delta^{\frac{\sigma-1}{\delta+1-\sigma}} \tilde{\alpha}_m \frac{a^N}{b^N \mu\left(q^N\right)} \frac{1}{\hat{\alpha}_h^N \left[\delta - \gamma\left(\sigma-1\right)\right] + \hat{\alpha}_m^N \left[\delta - \left(1-\gamma\right)\left(\sigma-1\right)\right]}. \tag{22}$$

The right hand side of this expression is unbounded above as $q^N \to 0$, strictly decreasing in q^N by Assumption 1 and converges to zero as $q^N \to 1$. Consequently, it determines a unique equilibrium q^N.

Conditional on q^N, equations (OS) and (IE) are two equations in w^S/w^N and q^S. Figure 6 plots these equations in $\left(q^S, w^S/w^N\right)$ space. The properties of $\mu\left(\cdot\right)$ ensure that the (IE) curve lies above the (OS) curve for q^S sufficiently close to zero, but below it for q^S sufficiently close to one. Since both curves are continuous in q^S, the existence of an equilibrium is guaranteed. Moreover, differentiating to obtain the gradients of the two curves and using Assumption 2 implies that at any equilibrium the (IE) curve cuts the (OS) curve from above. It follows that the two curves have a single crossing and their intersection determines the equilibrium values of w^S/w^N and q^S.

Next, substituting (21) into (18) yields:

$$\begin{aligned} w^N = & \left[\frac{1}{\sigma-1}\frac{1}{a^N}\left(\hat{\alpha}_h^N\left[\delta-\gamma\left(\sigma-1\right)\right]+\hat{\alpha}_m^N\left[\delta-\left(1-\gamma\right)\left(\sigma-1\right)\right]\right)\right]^{\frac{\delta+1-\sigma}{\delta(\sigma-1)}} \\ & \times\left(\frac{\sigma-1}{\sigma}\right)^{\frac{\sigma}{\sigma-1}}\left[\frac{L^N}{\delta}\left(1+\frac{w^S L^S}{w^N L^N}\right)\right]^{\frac{1}{\sigma-1}}\left[\frac{1}{f^N}\left(\gamma\hat{\alpha}_h^N\right)^{\gamma}\left[(1-\gamma)\hat{\alpha}_m^N\right]^{1-\gamma}\right]^{\frac{1}{\delta}}, \end{aligned} \tag{23}$$

which gives w^N as a function q^N and w^S/w^N. Finally, global consumption expenditure E is given by (21).

Now, let us turn to labor market clearing. A headquarters firm with a Northern supply chain employs a^N innovation workers and $f^N\left(z_h^N\right)^{\delta}$ knowledge transfer workers, where z_h^N is given by (5) with $A = E$, $w_m = w_h = w^N$, $f_m = f_h = f^N$, $\hat{\alpha}_h = \hat{\alpha}_h^N$ and $\hat{\alpha}_m = \hat{\alpha}_m^N$. Therefore, its total employment is $l_h^N = a^N + f^N\left(z_h^N\right)^{\delta}$. Similarly, a headquarters firm with a Southern supply chain has employment $l_h^S = a^N + \lambda f^N\left(z_h^S\right)^{\delta}$, where z_h^S is given by (5) with $A = E$, $w_m = w^S$, $w_h = w^N$, $f_m = \lambda f^S$, $f_h = \lambda f^N$, $\hat{\alpha}_h = \hat{\alpha}_h^S$ and $\hat{\alpha}_m = \hat{\alpha}_m^S$.

Supplier employment depends upon whether or not imitation occurs. Employment at the average Northern supplier is given by:

$$\mathbb{E}l_m^N = f^N\left(z_m^N\right)^{\delta} + \frac{(1-q^N)y_m^N + q^N\tilde{y}_m^N}{z^N},$$

where z_m^N is given by (5), y_m^N and $\tilde{y}_m^N$ are given by (3) and z^N is the technology of a Northern supplier given by (7) with $A = E$, $w_m = w_h = w^N$, $f_m = f_h = f^N$, $\hat{\alpha}_h = \hat{\alpha}_h^N$ and $\hat{\alpha}_m = \hat{\alpha}_m^N$. Likewise, average employment at Southern suppliers is:

$$\mathbb{E}l_m^S = \lambda f^S \left(z_m^S\right)^\delta + \frac{(1-q^S)y_m^S + q^S\tilde{y}_m^S}{z^S},$$

where z_m^S is given by (5), y_m^S and $\tilde{y}_m^S$ are given by (3) and z^S is the technology of a Southern supplier given by (7) with $A = E$, $w_m = w^S$, $w_h = w^N$, $f_m = \lambda f^S$, $f_h = \lambda f^N$, $\hat{\alpha}_h = \hat{\alpha}_h^S$ and $\hat{\alpha}_m = \hat{\alpha}_m^S$.

Imitators hire workers to undertake imitation and to produce inputs. It follows that a Northern imitator has employment $l_g^N = b^N\mu(q^N) + \tilde{y}_m^N/z^N$, while a Southern imitator has employment $l_g^S = b^S\mu(q^S) + \tilde{y}_m^S/z^S$.

Crucially, the expressions above imply that employment at all headquarters firms, suppliers and imitators is uniquely determined by the equilibrium values of w^S, w^N, q^S, q^N and E. All that remains is to solve for the equilibrium mass of headquarters firms M_h^N, Northern suppliers M_m^N, Southern suppliers M_m^S, Northern imitators M_g^N and Southern imitators M_g^S. Since all headquarters firms hire a supplier in either the North or the South we must have that:

$$M_h^N = M_m^N + M_m^S. \tag{24}$$

Labor market clearing in the North requires that L^N equals the sum of employment at headquarters firms with Northern supply chains, headquarters firms with Southern supply chains, Northern suppliers and Northern imitators. That is:

$$L^N = M_m^N l_h^N + M_m^S l_h^S + M_m^N \mathbb{E}l_m^N + M_g^N l_g^N, \tag{25}$$

and Southern labor market clearing requires:

$$L^S = M_m^S \mathbb{E}l_m^S + M_g^S l_g^S. \tag{26}$$

Given w^S, w^N, q^S, q^N and E, equations (24)-(26) together with equation (13) for $j = N, S$ form a system of five linear equations in the five unknowns M_h^N, M_m^N, M_m^S, M_g^N and M_g^S. Solving this system implies that the mass of Southern supplier is given by:

$$M_m^S = \frac{L^S}{\mathbb{E}l_m^S + q^S l_g^S},$$

and the mass of Northern suppliers is:

$$M_m^N = \frac{L^N - M_m^S l_h^S}{l_h^N + \mathbb{E}l_m^N + q^N l_g^N}.$$

Having obtained M_m^S and M_m^N, equation (24) gives M_h^N and equation (13) gives M_g^S and M_g^N.

This completes the proof that the offshoring model has a unique equilibrium. The proof assumes that headquarters firms hire suppliers in both countries and that there is no innovation in the South. Under what conditions do these assumptions hold? The expressions above for the mass of suppliers hired in each country imply that there will be a positive mass of suppliers in the North if and only if:

$$\frac{L^N}{L^S} > \frac{l_h^S}{\mathbb{E}l_m^S + q^S l_g^S},$$

which is satisfied provided L^N is sufficiently large relative to L^S.

There is no innovation in the South when the cost of innovation $a^S w^S$ exceeds the expected profits of setting up a headquarters firm in the South π_h^S. In equilibrium, Northern headquarters firms are indifferent between hiring suppliers in the North and South, even though international technology transfer is more costly than domestic technology transfer. It follows that a headquarters firm based in the South would always choose to hire a Southern supplier in order to avoid the costs of international technology transfer. Using this observation to calculate π_h^S implies that there is no innovation in the South if and only if:

$$a^S > \left[\frac{1}{\sigma - 1}\frac{1}{w^S}\left(\hat{\alpha}_h^S\left[\delta - \gamma\left(\sigma - 1\right)\right] + \hat{\alpha}_m^S\left[\delta - \left(1 - \gamma\right)\left(\sigma - 1\right)\right]\right)\right]^{\frac{\delta + 1 - \sigma}{\delta\sigma}} \\ \times \frac{\sigma - 1}{\sigma}\left(\frac{E}{\delta}\right)^{\frac{1}{\sigma}}\left[\frac{1}{f^S}\left(\gamma\hat{\alpha}_h^S\right)^{\gamma}\left[(1 - \gamma)\hat{\alpha}_m^S\right]^{1-\gamma}\right]^{\frac{\sigma - 1}{\delta\sigma}},$$

which holds provided a^S is sufficiently large.

Proof of Proposition 4

Equation (22) shows that q^N is independent of b^S, f^S and λ. The comparative statics for q^S and w^S/w^N then follow from equation (15) after noting that Assumption 2 gives $\chi_2 >$ and that:

$$
\begin{aligned}
(\delta + 1 - \sigma)\,\chi - [\delta\sigma - \gamma(\sigma - 1)]\,\chi_2 &= -(\sigma - 1)(\delta + 1 - \gamma)\chi_1, \\
&< 0,
\end{aligned}
$$

where the inequality follows from Assumption 1. Finally, equation (23) implies that b^S, f^S and λ affect w^N only through changes in w^S/w^N and that an increase in w^S/w^N raises w^N.

Proof of Proposition 5

The proposition follows immediately from inspection of equations (OS), (IE), (22) and (23).

Proof of Proposition 6

The key to proving this proposition is to observe that, conditional on the type of supply chain used, the equilibrium conditions are the same as in the baseline offshoring model. Start by considering the supply chain choice of Northern innovators that hire domestic suppliers and let $k = i, e$ subscripts denote the type of supply chain used.

Free entry into innovation and imitation in the North imply that equations (18) and (19) hold with $\gamma = \gamma_k$ and $\delta = \delta_k$ whenever firms use supply chains of type k. These equations determine the wage w^N, relative to $E^{\frac{1}{\sigma}}$, that is consistent with innovators and suppliers making zero expected profits, as a function of the imitation cost b^N. Conditional on global expenditure E, the wage w^N is strictly decreasing in b^N if $k = i$ and strictly increasing in b^N if $k = e$.

In equilibrium, innovators choose the supply chain type that delivers a higher Northern wage. Assuming that neither supply chain type is preferred for all levels of imitation risk, it follows that there exists $b^{N*} \in (0, \infty)$ such that innovators with Northern suppliers use exclusive supply chains if $b^N > b^{N*}$ and inclusive supply chains if $b^N < b^{N*}$. Both types of supply chain co-exist in equilibrium only in the knife-edge case where $b^N = b^{N*}$. The threshold b^{N*} is independent of the parameters of the Southern economy since equations (18) and (19) depend upon the South only through global consumption expenditure E, but E does not affect the threshold b^{N*} since it enters both equations symmetrically.

Conditional on supply chain choice in the North, an analogous argument using equations (OS) and (IE) shows that there exists a threshold b^{S*} such that Northern innovators that offshore input production to the South use exclusive supply chains if the Southern imitation cost $b^S > b^{S*}$ and inclusive supply chains otherwise. The Southern threshold depends upon shocks to the North through b^N, f^N and q^N.

Given supply chain choice in both countries, equilibrium is determined as in Proposition 3 and the wage effects of changes in b^S are as in Proposition 4.

Proof of Proposition 7

Innovators choose between open and secret research taking wages as given and anticipating free entry by imitators. Because imitators can choose to target suppliers of either open research or secret research firms, the endogenous imitation cost $\mu(\cdot)$ depends upon the ratio of imitators to suppliers by research type. Moreover, the imitation free entry condition (ME) that determines imitation risk (conditional on wages) holds separately for imitation of open research suppliers and imitation of secret research suppliers.

Assumption 3 implies that the (ME) curve is strictly downwards sloping, meaning that an increase in the imitation cost b reduces the equilibrium imitation risk q for a given wage level. Expected profits from innovation are given by equation (8) and are increasing in imitation risk for inclusive value chains, but decreasing in imitation risk for exclusive value chains. Consequently, when value chains are inclusive, innovators choose open research in order to reduce the imitation cost to $\left(1-\zeta^b\right)b$ and maximize imitation risk. But when value chains are exclusive, innovators prefer secret research in order to minimize imitation risk.

Absent knowledge spillovers, the choice between open and secret research only affects imitation costs and part (i) of Proposition 2 implies that innovators' choices maximize real wages and welfare in both inclusive and exclusive value chains.

When there are knowledge spillovers, innovation costs also adjust. Assumptions 1 and 3 together give $\chi - \chi_1 = \chi_3 < 0$. Therefore, equation (14) implies that wages are decreasing in the cost of innovation. It follows that innovators' choice of open research in inclusive value chains is socially optimal, but their choice of secret research in exclusive value chains has a negative wage externality. When $\zeta^a = \zeta^b$, open research is equivalent to balanced technical change, which raises wages in both inclusive and exclusive value chains by part (iii) of Proposition 2.