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Geopolitical Frictions and Technology Transfers: Theory and Empirics[†]

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Abstract: How do geopolitical frictions matter for the diffusion of technology? Based on a guns-versus-butter model involving two countries (a technology leader and a technology laggard), we study the direct and indirect effects dual-use (or general-purpose) technology transfers on the countries' payoffs and hence their preferences over such transfers. A central finding is that, when the initial technological distance between the two countries is large whereas the degree of output security is low and the laggard's capacity to absorb state-of-the-art technologies is relatively limited, the leader has an incentive to block a transfer to the laggard. The analysis also unveils the possible emergence of a "low-technology trap."Using data on cross-border patent flows as a proxy for technology transfers and sanctions as a proxy for conflict over the 1995–2018 period, we present evidence in support of the theory.

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1 Introduction

In the midst of ongoing geopolitical tensions between the U.S. and China lie concerns about China's actual or potential use of American technology to further its own military objectives. While U.S. trade and investment relations with China have always been formulated with national security issues in mind, the expansion of technologies having both military and civilian applications has introduced new complexities (Olson, 2019). Indeed, heightened by China's alleged practice of "forced technology transfers" and by its recent policy shift to foster dual-use infrastructure and resource sharing between the military and civil government, research institutes, and companies, these concerns have prompted the U.S. to impose sanctions on China.[1] Likewise, even before Russia's invasion of Ukraine, the U.S. imposed a series of sanctions intended to block access by Russia's defense sector to western technologies in the aerospace, marine, and electronic sectors, that allegedly facilitate dual-use technology.[2] The most direct consequence of such sanctions would seem clear enough—that is, to limit the transfer of technology. But, although the benefits of technology transfers on productivity have been widely studied, less is known about their potential drawbacks based on security considerations. Could the possibility of a future conflict between countries make technology transfers so costly as to render them undesirable and thus make sanctions appealing? Shedding light on this issue has important policy implications insofar as the diffusion of technology is a significant factor that explains variation in income levels across countries (e.g., Parente and Prescott, 1994; Caselli and Wilson, 2004).

This paper examines both the desirability and feasibility of technology transfers in a setting where geopolitical frictions are present. To fix ideas though without loss of generality, we suppose such frictions stem from imperfect transnational institutions governing the security of output or income. More precisely, building on a single-period, guns-versus-butter model involving two countries (a technology leader and a technology laggard), our analysis identifies the conditions under which a transfer of dual-use (or general-purpose) technology enhances global efficiency and the conditions under which one country chooses to block such

[1] These sanctions were imposed under the Trump administration in November 2020 with Executive Order (E.O.) 13959, and were subsequently broadened by the Biden Administration in June 2021 with E.O. 14032. According to Sykes (2021), although the notion of "forced technology transfers" encompasses involuntary transfers through the actual theft of intellectual property (e.g., corporate espionage), it also includes more consensual sorts of transfers through the application of "corporate structure requirements" (CSRs), which require foreign investors to form a joint venture with Chinese firms or give them a controlling equity stake; CSRs effectively allow Chinese firms to demand a technology transfer as a condition for establishing a partnership. See the U.S. Department of State's interpretation of China's recent policy, once called the "Chinese Civic-Military Fusion policy": https://www.state.gov/wp-content/uploads/2020/05/What-is-MCF-One-Pager.pdf. In October 2022, the Biden administration imposed new and more comprehensive restrictions on the sale of U.S. semiconductor technology (having military applications) to China (see https://www.nytimes.com/2022/10/07/business/economy/biden-chip-technology.html).

[2] These sanctions were authorized in April 2021 with E.O. 14024 and extended in March 2022 as described in the U.S. Treasury's press release: https://home.treasury.gov/news/press-releases/jy0692.

a transfer. Both sets of conditions depend on the initial difference in countries' technology and the likelihood of future conflict or, equivalently, the degree of output security.

The model is structured as a two-stage, complete-information game. In stage 1, the technology leader declares its willingness to make its superior dual-use technology available to the laggard (perhaps at some exogenously determined cost). At the same time, the laggard announces its willingness to accept this technology. The transfer is implemented if both sides agree to it, and it is not if at least one country objects. In stage 2, countries choose simultaneously how to allocate their respective resources to the production of butter (or consumables) and to the production of guns (or arms). Peace and conflict occur probabilistically. In the event of peace, each country consumes its own output and the guns previously produced have no value. In the event of conflict, the two countries use their guns to compete for a share of total output produced by both of them.

As in the canonical guns-versus-butter framework with decisions made by each country to maximize its expected payoff, the allocation of resources to guns is motivated by imperfect security of output or butter. Specifically, in our setting, if peace were certain and thus output were perfectly secure (or more generally geopolitical frictions were absent), no resources would be allocated to guns and neither country would object to technology transfers. But, the possibility of conflict implies imperfect output security and induces countries to arm. What's more, each country's arming decision depends not only on the *ex-ante* degree of output security (or the probability of peace), but also on the levels of technology that both countries possess.

In accordance with the subgame-perfect, Nash equilibrium concept, we first characterize the outcome of the second stage in terms of arming choices and expected payoffs as they depend on the technological distance between the two counties and the *ex-ante* degree of output security. Unsurprisingly, an exogenous improvement in the laggard's dual-use technology generates a positive direct payoff effect for both countries. This payoff effect, which treats arming choices as fixed, is in terms of increased output and thus a larger prize in the potential conflict between them. But, the exogenous improvement in the laggard's technology also generates negative indirect (or strategic) payoff effects, as it amplifies both countries' arming incentives. For the laggard, this negative effect is always dominated by the positive (direct) effect. However, the opposite can hold true for the leader. In particular, when their technological distance is large initially and the *ex-ante* degree of output security is sufficiently low, the laggard employs such improvements intensively in the production of guns such that the resulting strategic effect dominates, thereby reducing the leader's payoff.

The analysis also shows that, while exogenous improvements in the *ex-ante* degree of output security never decrease the leader's payoff, they could decrease the laggard's payoffs. A necessary condition for this outcome is that the distance between the laggard's and the leader's technology is sufficiently large.

Interestingly, the results described above hint at the possibility of a "low-technology trap," wherein a country that starts out at a low level of technology remains in such a state because the more technologically advanced country (a potential adversary) chooses to block a technology transfer.[3] To explore this possibility further, we study the equilibrium of the extended game of technology transfers, drawing from our analysis of how exogenous improvements in technology and security affect arming and, consequently, payoffs. Along the lines of the technology transfer literature surveyed by Keller (2004), the analysis admits the possibility that the laggard's capacity to implement the superior technology held by the leader might be limited. We find that a low-technology trap is more likely to arise when, given the degree of output security, the technological distance between countries is sufficiently large to start and when the limits on the laggard's ability to absorb state-of-the-art technology are greater.

While the process by which technology is diffused is much more complicated than the way we have captured it theoretically in this paper, likely depending on trade and especially foreign direct investment (e.g., Keller, 2004; Anderson et al., 2019; Perla et al., 2021), we chose to abstract from such interactions in our analysis to isolate the effects of imperfect output security on the desirability and feasibility of technology transfers. Nonetheless, it is worth pointing out how some of our findings mirror previous results in the literature on the welfare effects of productivity improvements. Samuelson (2004), for example, demonstrates that technological progress in a less developed nation can reduce the technology leader's welfare. By contrast, Jones and Ruffin (2008) find, in a different setting, that the leader might gain from transferring the technology from its exporting sector to another country. Taken together, these results are close to our finding that technology transfers can potentially increase or decrease the leader's payoffs. However, in those papers, the welfare effects of productivity improvements operate through a terms-of-trade channel, whereas the effects we identify here are due to insecurity and operate through arming decisions.

It is also worthwhile to point out an important distinction between the transfers of technology we consider here and resource transfers intended to support peace as an endogenous outcome. For example, in Garfinkel and Syropoulos (2021) who study peace as the preservation of the status quo, it is the less affluent country that tends to have an incentive to arm and declare war (modeled as a "winner-take-all contest") against its richer rival, since it perceives a larger potential gain from doing so. Naturally, a transfer of resources (a rival

[3] This self-reinforcing outcome, which is related to (but distinct from) a poverty trap, can be viewed in our analysis as the result of the failure of international institutions to support perfect output security. See the survey on poverty traps by Azariadis and Stachursky (2005). Also, see Gonzalez's (2012) insightful discussion of why imperfect property rights are problematic for economic development and why they tend to persist over time in less developed countries.

and excludable good) made by the richer country has the effect of evening out the distribution of endowments and, therefore, reduces the potential relative gain from war for the less affluent country.[4] While a transfer of technology (a non-rival but excludable good), by contrast, does not imply a direct loss of technological know-how for the donor, it evens out the two countries' capabilities. Nonetheless, such a transfer tends to induce both countries to arm by more, thereby raising the resource cost of conflict between them.

Our analysis is related to a number of earlier papers that highlight the effects of rent-seeking activities to hinder the development and adoption of new technologies and products. For example, Parente and Prescott (1999) show how monopoly rights held by labor raise the costs and thus reduce the incentive of firms to adopt a superior technology.[5] Along similar lines, Desmet and Parente (2014) argue that craft guilds in Europe blocked technological progress and economic growth before the 18th century; but eventually, as markets expanded, firms' profits became sufficiently large to overcome the guilds' resistance to new technologies. With a different focus in the context of an R&D-based growth model, Dinopoulos and Syropoulos (2007) explore how incumbent firms can safeguard their monopoly rents due to their past innovations through costly activities that slow down the rate by which other firms successfully innovate to become the new incumbents. We contribute to this literature by suggesting a complementary barrier to technological progress—namely, costly measures taken to establish property rights over output in preparation for a possible conflict.

But, our analysis is closest to Gonzalez (2005), who similarly studies the role of appropriative conflict in understanding why superior technologies might not be adopted by laggards, and can be seen as complementing his analysis in several ways. Most importantly, while we study a dual-use technology that directly affects the abilities of the contenders to arm as well as to produce goods for (civilian) consumption, he studies a technology that is effectively sector specific, designed to affect the production of only consumables. In addition, whereas our focus is on the interactions between a technology leader and a technology laggard, Gonzalez (2005) focuses on the interactions between two laggards, initially endowed with identical inferior technologies, that simultaneously choose between adopting the superior technology or sticking with the inferior one. His finding that, in equilibrium depending on parameter values, neither agent chooses the superior technology or maybe

[4] Garfinkel and Syropoulos (2020) show a more affluent country could "burn" its own resources to similarly support peace, but this alternative is Pareto dominated by offering a resource transfer.

[5] See Atkin et al. (2017) who present experimental evidence suggesting that misaligned incentives between workers and firm owners prevented the adoption of a superior technology among soccer-ball producers in Pakistan. In a related analysis similarly emphasizing the winners and losers of innovation, Krusell and Ríos-Rull (1996) develop a dynamic, political economy model wherein those that benefit from the current technology might attempt to block the adoption of superior technologies, with the outcome depending on the distribution of skills among voters. More recently, Milner and Solstad (2021) study how government policies that influence the adoption of new technologies depend not only on domestic politics, but also international factors including global competition and relations with other countries.

just one does (but never both), points to the possibility of technological backwardness. By contrast, our finding points to the possible persistence of differences in technological know-how across agents.[6] Furthermore, our simple parameterization of insecurity allows us to study how the degree of imperfect property rights determines countries' arming choices and payoffs, and ultimately the diffusion of technology.

With a focus on the model's key predictions, we also present some evidence using cross-border patents flows, as a proxy for technology transfers, during the 1995–2018 period. The empirical analysis takes LaBelle et al.'s (2025) empirical model of such flows as its starting point, relying on well-established estimation practices from the gravity literature. The analysis departs from LaBelle et al. (2025) by distinguishing between technology leaders and laggards and introducing covariates motivated by the theoretical analysis that are novel relative to the empirical literature: measures of conflict, technological distance between the leader and the laggard, and the laggard's ability to absorb technology. Our estimates show that the frequency of bilateral technology transfers from leaders to laggards is smaller on average than all other technology transfers—that is, between leaders, between laggards and from laggards to leaders—in the presence of conflict, when the technological distance between leaders and laggards is greater and when the laggard's absorptive capacity is smaller. These findings, which are robust to alternative proxies of conflict and methods of distinguishing between leaders and laggards, complement existing empirical analyses of the determinants of technology transfer and bilateral patent flows.[7]

In what follows, the next section describes the theoretical model of output disputes used to explore the countries' incentives to arm, given the technology difference between them and the probability that a dispute over the distribution of their joint output arises. Section 3 studies how exogenous improvements in the dual-use technology and in *ex-ante* output security matter for countries' arming choices, their payoffs and global efficiency. In Section 4, we turn to the first stage of the game to consider the possibility of technology transfers, demonstrating the possible emergence of a low-technology trap. Section 5 presents the empirical evidence. Finally, in Section 6, we offer some concluding remarks, including possible extensions of the analysis. Technical details appear in appendices.

[6] As discussed below, one can study, within a slightly modified version of the framework of the present paper, international differences in the sector-specific technology that governs the production of consumables alone. While only the laggard in this case might have an incentive to turn down an offer by the leader for a transfer of its superior civilian production technology, the conditions under which that happens are similar to those that are conducive to the emergence of a low-technology trap.

[7] This relatively small but recent and growing literature includes, for example, Brunel and Zylkin (2022) and De Rassenfosse et al. (2022), who show that cross-border patents are more likely to be obtained by innovators where more trade is anticipated. Santacreu (2024) and Hemous et al. (2023) study the links between improvements in intellectual property protection and technology transfers, while Martınez-Zarzoso and Arregui Coka (2025), Coleman (2022) and Howard, Maskus, and Ridley (2025) examine how trade agreements and intellectual property right provisions affect bilateral patent flows. (See LaBelle et al. (2025) for a more extended discussion of the relevant literature.)

2 A Model of Output Disputes

Consider an environment with two risk-neutral countries $i = 1, 2$. Each country i holds a secure endowment of R^i units of a resource ("labor") that it can allocate to the production of arms (or "guns") and a consumption good ("butter"). We assume these countries have solved their collective action problems, so that each country's decision maker acts in the interests of its respective country as a whole.[8]

A key feature of the model is that it allows for possible differences across countries with respect to a dual-use or general-purpose technology, reflected in the parameter $\alpha^i > 0$, that transforms country i's resource endowment R^i into its "effective endowment" or human capital, $H^i = \alpha^i R^i$, and is equally applicable to activities that are socially valuable (producing butter) and to activities that are redistributive (producing guns). This technology would be positively related to the country's infrastructure, educational system, healthcare, the quality of its institutions, and so on. To be more precise, let G^i and X^i denote country i's output of guns and butter, respectively, and suppose that the technology exhibits constant returns to scale. Country i's resource constraint implies that, for any quantity of guns produced $G^i \in [0, H^i]$, the maximal quantity of butter is $X^i = H^i - G^i$.[9] To fix ideas, we assume henceforth that country 1 is more productive in the sense that $\alpha^1 > \alpha^2$. For obvious reasons, we will refer to country 1 as the technology leader and country 2 as the technology laggard.

To study the importance of imperfect output security, suppose the distribution of total output, $\bar{X} \equiv \sum_{i=1,2} X^i$, for consumption by the two countries depends in part on whether peace prevails or a conflict emerges between them. In the event of peace, which occurs with an exogenously given probability $\sigma \in [0, 1)$, each country i consumes its entire output X^i; but, with probability $1 - \sigma \in (0, 1]$, a conflict emerges where each country i's butter X^i goes into a common pool $\bar{X}$ that is contested. The probability of peace σ—or, equivalently, the *ex-ante* degree of output security—would depend on a number of factors including formal and informal international institutions of governance that mediate and govern disputes.[10]

In the event of conflict, country i's share of $\bar{X}$ depends on both countries' previously

[8] Alternatively, the model can be thought of capturing the interactions between individuals or groups of individuals (that again have solved collective action problems) within a single country.

[9] Country i's resource constraint can equivalently be written as $H^i = \alpha^i R^i = X^i + G^i$, which implies X^i/α^i units of R^i are required to produce X^i units of butter and G^i/α^i units of R^i are required to produce G^i units of guns; furthermore, changes in α^i that indicate changes in country i's effectiveness in transforming R^i (α^i) into butter and guns are isomorphic to changes in R^i.

[10] Under the interpretation of agents as groups of individuals within a country, σ would depend on domestic institutions that consist of regulatory and enforcement agencies, the police and the court system. Multiple studies have found reduced-form evidence that the quality of institutions is positively related to per-capita income (e.g., Acemoglu et al., 2001) and that differences in institutions and government policies explain some of the variation in productivity levels across countries (e.g., Hall and Jones, 1999). Also, see Rodrik et al. (2002), who find that institutions contribute more to per-capita income than trade and geography.

made arming according to the following conflict technology:

$$\phi^i \equiv \phi^i\left(G^i, G^j\right) = \begin{cases} G^i/\bar{G} & \text{if} \quad \bar{G} > 0 \\ X^i/\bar{X} & \text{if} \quad \bar{G} = 0 \end{cases}, \quad i, j \in \{1, 2\},\ i \neq j, \tag{1}$$

where $\bar{G} \equiv \sum_{i=1,2} G^i$ denotes aggregate arming across the two countries. The function in (1) has a number of important properties.[11] First, it is symmetric in the sense that neither country has a technological advantage in conflict: $\phi^i(G^i, G^j) = \phi^j(G^i, G^j)$ for $i, j \in \{1, 2\},\ i \neq j$. Second, each country's share ϕ^i depends positively on its own guns G^i, with a diminishing marginal effect (i.e., $\phi^i_{G^i} > 0$ and $\phi^i_{G^iG^i} < 0$). By contrast, each country's share ϕ^i depends negatively on rival's guns G^j, though again with a diminishing marginal effect (i.e., $\phi^i_{G^j} < 0$ and $\phi^i_{G^jG^j} > 0$). Finally, whether an increase in the rival's guns G^j positively or negatively affects the magnitude of an increase on a country's guns G^i on its own share $\phi^i_{G^i}$ depends on the ranking between G^i and G^j; specifically, $\phi^i_{G^iG^j} \gtreqless 0$ holds as $G^i \gtreqless G^j$. These properties, along with our specification of payoffs below, ensure the existence of a unique subgame perfect equilibrium in arming.[12]

Under risk neutrality, each country i's (expected) payoff is defined as

$$U^i\left(G^i, G^j\right) = (1-\sigma)\,\phi^i \bar{X} + \sigma X^i, \ \ i, j \in \{1, 2\},\ i \neq j, \tag{2}$$

for all $G^i \in [0, H^i]$, where $\phi^i = \phi^i(G^i, G^j)$ is shown in (1) while $X^i = H^i - G^i$ and $\bar{X} = \sum_{i=1,2} X^i$, as previously defined.[13] The first term in the right-hand side (RHS) of (2) reflects country i's payoff conditional on conflict, equal to the portion of the contested pool $\bar{X}$ that is appropriated by country i on the basis of its relative strength captured by ϕ^i. The second term reflects country i's payoff conditional on peace that equals its own output X^i. Since an increase in country i's guns G^i diverts human capital away from its butter production, X^i falls with increases in G^i causing its payoff U^i to fall. However, an increase in G^i also raises country i's share ϕ^i of contested butter in the event of conflict,

[11] This specification differs slightly from that which has been axiomatized by Skaperdas (1996) in that here, when $G^1 = G^2 = 0$, the conflict preserves the status-quo distribution of output. This modification, however, is inconsequential for the equilibrium analysis.

[12] Owing to our assumption that countries are risk neutral, the conflict we study could be interpreted equivalently as a "winner-take-all" contest over $\bar{X}$, with ϕ^i representing the probability that country i emerges as the victor. Our interpretation of ϕ^i as country i's share of $\bar{X}$ in the event of conflict could be thought of as a reduced form of bargaining. Indeed, the key insights of our analysis would remain intact if the contested butter were divided on the basis of Nash bargaining or other bargaining protocols in the shadow of destructive war (e.g., Anbarci et al., 2002).

[13] Due to our assumption of risk neutrality, the game described here is analytically equivalent to one where conflict emerges with probability 1 and σ denotes the fraction of butter produced by each country that is secure; in this case, the pool of butter contested in that (certain) conflict would equal $(1-\sigma)\bar{X}$. However, the analysis could be extended to allow for risk aversion. As in our current setup, the key mechanism through which technology transfers matter would be the resolution of actual or potential conflict that depends on the countries' relative arming decisions.

and U^i is increasing in G^i on this count. Clearly, for any given G^j ($j \neq i$), an optimally behaving country i chooses its guns to balance the marginal benefit of arming against the corresponding marginal cost.[14] Of course, the payoff for each country i also depends on country j's arming choice. In particular, for any given and feasible G^i, an increase in the rival country j's guns G^j reduces U^i (i.e., $U^i_{G^j} < 0$ for $i, j \in \{1, 2\}$, $i \neq j$), because it reduces country j's contribution (X^j) to global output ($\bar{X}$) that would be contested in the event of conflict and because it reduces country i's share ϕ^i of $\bar{X}$ in that event.

Our central objective is to characterize the subgame perfect equilibrium of the following two-stage game.

Stage 1: The technology leader declares whether it will make its technology available to the laggard at some exogenously determined cost that could be bilateral, while the laggard declares whether it would accept this technology.

Stage 2: Given the first-stage choices, the countries choose their guns simultaneously and noncooperatively to maximize their respective expected payoffs.

Naturally, the two countries factor in how a transfer of knowledge in the first stage affects second-stage choices that, in turn, affect the distribution of global output and thus their respective expected payoffs.

To help frame the analysis, let us first consider what would happen if peace were certain ($\sigma = 1$), so that butter output is perfectly secure. One can easily verify that, in this hypothetical case that we refer to as "Nirvana," neither country would have an incentive to arm. Accordingly, each country i would devote its entire effective endowment H^i to the production of butter, so that $U^i_n = H^i = \alpha^i R^i$ for $i = 1, 2$ (the subscript "n" stands for "Nirvana"). In the presence of perfect output security, then, the more efficient/productive country would be indifferent between (freely) sharing and not sharing its superior expertise. By contrast, the relatively inefficient/unproductive country would necessarily value having access to the leader's superior technology. As we will see shortly, the possibility of conflict that implies imperfect output security motivates the two countries to arm and, in turn, can alter their preferences over technology transfers relative to the Nirvana benchmark.

3 How Dual-Use Technology Matters

In this section we characterize the equilibrium of the arming subgame whereby we can deepen our understanding of how technology matters for payoffs. To fix ideas, assume that, while $\alpha^2 < \alpha^1$, global resources endowments are evenly distributed across the two countries: $R^i = \frac{1}{2}\bar{R} = 1$ ($i = 1, 2$), which implies $H^1 = \alpha^1$, $H^2 = \alpha^2$ and $\bar{H} \equiv \sum_{i=1,2} H^i = \alpha^1 + \alpha^2$.[15]

[14] Allowing for the possibility that conflict destroys some fraction of both secure and insecure output would not affect equilibrium gun choices, but of course would affect payoffs.

[15] As noted below, allowing for the possibility that $R^1 \neq R^2$ does not alter our key results substantively.

The impact of an increase in α^2 given α^1 (which could arise due to technology transfers) operates through the implied changes in the effective resource endowments H^2 and $\bar{H}$. We study first how differences in the dual-use technology across countries matter for arming choices and then how they matter for payoffs.

3.1 Arming

Imposing the assumptions mentioned above on (2) and partially differentiating the resulting expression with respect to G^i yield

$$U^i_{G^i} = (1-\sigma)\,\bar{X}\phi^i_{G^i} - \left[\sigma + (1-\sigma)\,\phi^i\right],\ i = 1, 2. \tag{3}$$

The first term in the RHS of (3) shows country i's marginal benefit of arming (MB^i_G) due to the implied increase (given the opponent's choice G^j) in the share of total output $\bar{X} = \bar{H} - \bar{G}$ it secures in the event that conflict emerges. Notice that an increase in either α^i or α^j, given arming choices, increases $\bar{X}$ and thus amplifies MB^i_G. The second term in (3) shows the marginal cost of arming (MC^i_G) resulting from the implied diversion of the country's resources away the production of butter. MC^i_G is independent of α^i and α^j, implying that the net marginal benefit of arming ($U^i_{G^i}$) is increasing in the dual-use technology parameters. The expression in (3) also shows that an increase in the *ex ante* degree of security σ reduces MB^i_G, raises MC^i_G (since $\phi^i < 1$) and hence reduces $U^i_{G^i}$.

Based on (3) and the resource constraint $G^i \in [0, \alpha^i]$, we can write each country i's (possibly constrained) best-response function, labeled $B^i(G^j)$, as:

$$B^i\left(G^j\right) = \min\left\{\widetilde{B}^i\left(G^j\right), \alpha^i\right\}, \quad i, j \in \{1, 2\},\ i \neq j, \tag{4a}$$

where $\widetilde{B}^i(G^j)$ represents country i's unconstrained best response that is implicitly defined by $U^i_{G^i} = 0$:

$$\widetilde{B}^i\left(G^j\right) = -G^j + \sqrt{(1-\sigma)\,G^j(\alpha^i + \alpha^j))}, \quad i, j \in \{1, 2\},\ i \neq j. \tag{4b}$$

When neither country is constrained in its arming choice, the unconstrained best-response functions (4b) intersect at the following unique interior solution:

$$\widetilde{G}^i = \widetilde{G} \equiv \tfrac{1}{4}(1-\sigma)(\alpha^1 + \alpha^2), \text{ for } i = 1, 2, \tag{5}$$

which is increasing in α^1 and α^2, but decreasing in the *ex ante* degree of security σ. The expression in (5) implies that there exists a unique threshold value of α^2, conditioned on the leader's technology α^1 and the *ex-ante* degree of output security σ, above which neither country is resource constrained in its arming choice (i.e., $\widetilde{G} < H^2 = \alpha^2$), such that the solution shown in (5) indeed represents the equilibrium in the arming subgame. This threshold, labeled $\alpha_0(\sigma)$, is given by

$$\alpha_0(\sigma) \equiv \frac{1-\sigma}{3+\sigma}\alpha^1, \tag{6}$$

where $\alpha_0'(\sigma) < 0$, with $\alpha_0(0) = \alpha^1/3$ and $\alpha_0(1) = 0$.

In drawing out the implications, we use a superscript "*" to indicate equilibrium values of variables. If $\alpha^2 \in (\alpha_0(\sigma), \alpha^1]$ which is more likely to hold as σ increases, then $G^{1*} = G^{2*} = \widetilde{G} < \alpha^2$ as shown in (5), implying that both countries produce butter as well as guns.[16] Alternatively, if $\alpha^2 \in (0, \alpha_0(\sigma)]$ which implies $\widetilde{G} > \alpha^2$, then the laggard becomes a pure predator, specializing in guns production: $G^{2*} = \alpha^2$; in turn, (4b) implies $G^{1*} = \widetilde{B}^1(\alpha^2) = -\alpha^2 + \sqrt{(1-\sigma)\alpha^2(\alpha^1+\alpha^2)}$. As one can easily verify, $G^{1*} < \alpha^1$ holds in this case, implying that both countries cannot be pure predators.[17]

We can now establish the following proposition based on the above:

Proposition 1 (Arming and power.) *Assuming imperfect output security ($\sigma < 1$), the unique equilibrium of the arming subgame implies that the technology leader is at least as powerful as the laggard (i.e., $\alpha^2 < \alpha^1$ implies $\phi^{1*} \geq \phi^{2*}$), and is strictly more powerful when the laggard is resource constrained. Given α^1 ($> \alpha^2$):*

(a) *Improvements in the laggard's dual-use technology ($\alpha^2 \uparrow$) induce both countries to arm more heavily, with the following implications for the balance of power:*

  (i) *When the laggard is resource constrained in its arming choice, it increases its guns by more than the leader, thereby improving its power ($\phi^{2*} \uparrow$).*

  (ii) *When the laggard is not resource constrained, the two countries make identical adjustments in arming choices and remain equally powerful (i.e., $\phi^{1*} = \phi^{2*}$).*

(b) *Improvements in security ($\sigma \uparrow$) reduce the leader's or both countries' incentives to arm given the rival's choice, with the following implications for the balance of power:*

  (i) *When the laggard is resourced constrained, the leader chooses fewer guns, thus eroding the leader's power advantage ($\phi^{1*} \downarrow$).*

  (ii) *When the laggard is not resource constrained, the two countries reduce their guns identically, thus leaving them equally powerful (i.e., $\phi^{1*} = \phi^{2*}$).*

The equilibrium in arming characterized in Proposition 1 is illustrated by point E in Fig. 1(a) where the countries' best-response functions intersect each other, in the special case of totally insecure output (i.e., $\sigma = 0$) and technologically symmetric countries (i.e., $\alpha^1 = \alpha^2$).

[16] Since $\alpha_0(0)$ ($= \alpha^1/3$) equals the maximum value that this threshold can take on for $\sigma \in [0, 1)$, any value of $\alpha^2 > \alpha_0(0)$ ensures that the interior solution in (5) emerges as the equilibrium of the arming subgame.

[17] As one can easily confirm, $\widetilde{B}^1(G^2)$ reaches a maximum where the laggard is not resource constrained. Accordingly, the technology leader chooses fewer guns and produces more butter when its rival produces no butter than when its rival produces some butter.

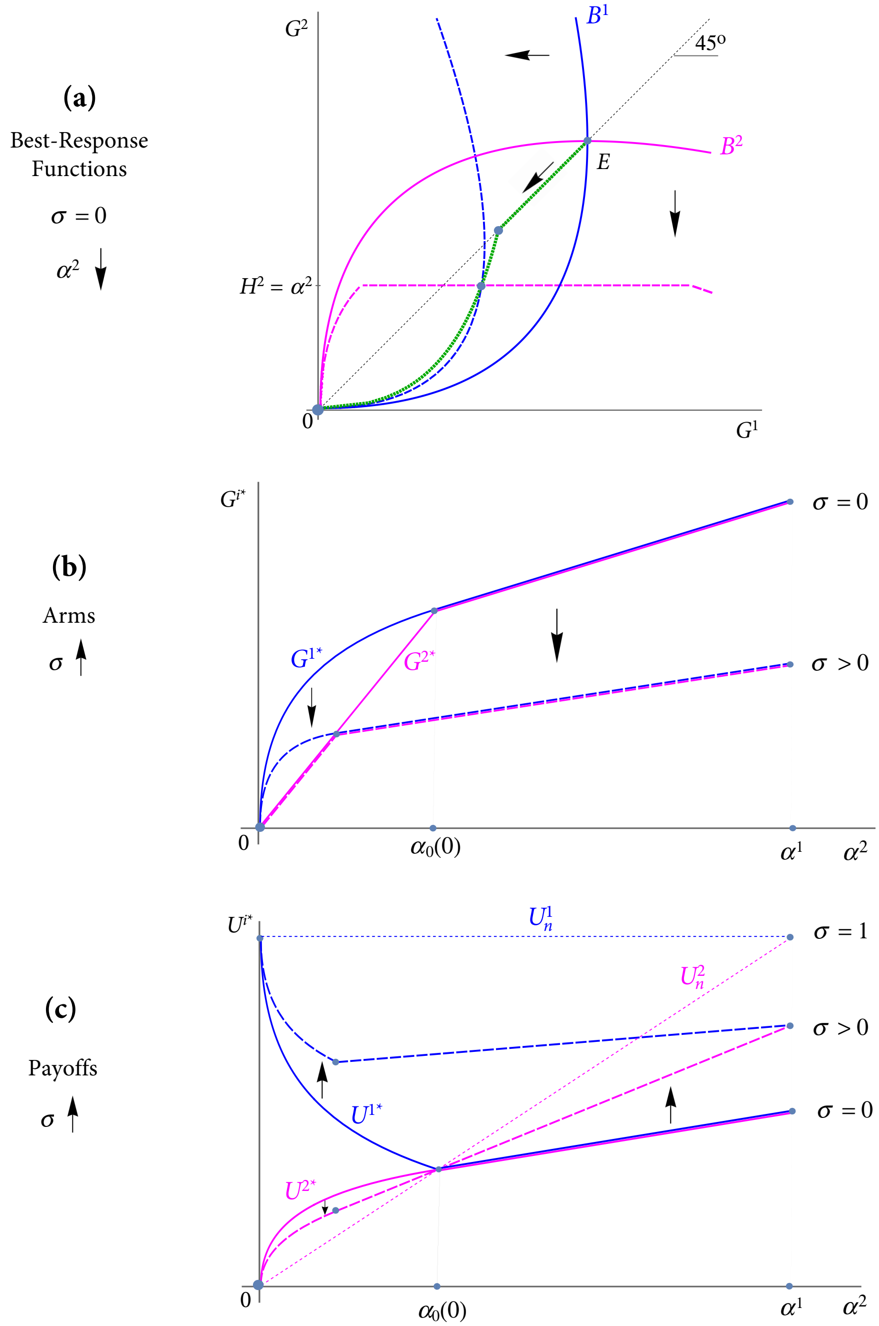

Figure 1: The Importance of Dual-Use Technology Differences and *Ex-Ante* Security for Arming and Payoffs

By the definition of equilibrium and due to complete symmetry in this benchmark case, point E lies on the 45°. The thick dotted green curve depicts the equilibrium pairs of guns that emerge for alternative values of α^2 (specifically, for technological regress associated with reductions in α^2 from α^1 towards 0). As shown in the figure, such regress that causes the value of the "prize" to fall induces each country to reduce its best response to any given arming choice by its rival. Initially, the shifts are symmetric so that the equilibrium remains symmetric and accordingly located on the 45° line, but closer to the origin. Hence, differences in the dual-use technology need not imply differences in arming and power across countries. However, when α^2 falls below the threshold $\alpha_0(\sigma)$ so that the laggard's resource constraint binds, the shifts become asymmetric. In particular, the laggard begins to specialize completely in appropriation; and, any additional reduction in α^2 brings about a one-for-one reduction in G^{2*}.[18] The technology leader's best-response function shifts inward; and, since its own secure endowment has not changed, its production necessarily remains diversified. These adjustments, together with the strategic complementarity of G^1 for G^2 in the neighborhood of the constrained equilibrium, ensure that G^{1*} falls. However, as established in part (a.i) of the proposition and as indicated by the shape of the green locus, G^{1*} falls by less than G^{2*} $(= \alpha^2)$ to induce a continuous rise in ϕ^{1*} above $\frac{1}{2}$.

The equilibrium adjustments in guns described above as α^2 varies are illustrated in Fig. 1(b) for two distinct values of the *ex-ante* degree of security σ: $\sigma = 0$ and a value of $\sigma \in (0, 1)$. Proposition 1(b) shows that improvements in *ex-ante* security ($\sigma \uparrow$) always induce the technology leader ($i = 1$) to produce fewer guns. The same is true for the laggard ($i = 2$) except, of course, when its effective endowment is exhausted by its production of guns. In the former case where neither country is resource constrained, such improvements have no effect on the balance of power; otherwise, they reduce the leader's power. Nonetheless, in both cases provided that security is imperfect, Hirshleifer's (1991) paradox of power holds. That is to say, the laggard devotes a disproportionately larger share of its effective endowment to arming than its rival such that $1 \geq G^{2*}/G^{1*} > \alpha^2/\alpha^1$.

3.2 Payoffs

It should be clear from the above analysis of the two countries' arming that the leader always obtains a higher payoff than the laggard: $U^{1*} > U^{2*}$ as $\alpha^1 > \alpha^2$. Specifically, when the laggard is resource constrained, the leader's arming is greater than its rival's arming, such that its share of the prize is larger (i.e., $\phi^{1*} > \phi^{2*}$) in the event of conflict. Furthermore,

[18] That the laggard specializes in guns production when $\alpha^2 < \alpha_0(\sigma)$ is due to the linear structure of the model. As shown in Appendix A.2 with more technical details provided in Online Appendx B, the laggard always produces butter as well as arms when we allow for complementary inputs (or, equivalently, diminishing marginal returns of $\alpha^i - G^i$) in butter production; and, the welfare effects we derive below in our simpler setting remain intact.

the leader (in contrast to the laggard) always devotes some of its effective endowment to the production of butter, which it enjoys in the event of peace (i.e., $X^{1*} > X^{2*} = 0$). Even if the laggard is not resource constrained so that the two countries produce identical quantities of guns and thus secure equal shares of contested output in the event of conflict (i.e., $\phi^{1*} = \phi^{2*}$), the leader's effective endowment is larger (i.e., $X^{1*} > X^{2*} > 0$), implying that its payoff conditional on peace is necessarily larger.

To examine the payoff effects of improvements in the laggard's technology, we start with the leader. Having established that the leader is never resource constrained in its arming choice such that $U^{1*}_{G^1} = 0$, we can differentiate (2) for $i = 1$ with respect to α^2 and evaluate the resulting expression at the equilibrium of the arming subgame as follows:

$$\frac{dU^{1*}}{d\alpha^2} = U^{1*}_{\alpha^2} + U^{1*}_{G^2}\left(\frac{dG^{2*}}{d\alpha^2}\right). \tag{7}$$

The first term in the RHS of (7) shows the direct effect of a change in α^2 on 1's payoff:

$$U^{1*}_{\alpha^2} = (1-\sigma)\,\phi^{1*} > 0. \tag{8a}$$

The inequality follows from the effect of an increase in α^2, for given guns, to expand the laggard's effective resource endowment, thereby inducing it to contribute more butter to the common pool $\bar{X}$. The second term in the RHS of (7) represents the indirect (or strategic) effect through the impact on rival 2's arming, where

$$U^{1*}_{G^2} = (1-\sigma)\left(\phi^{1*}_{G^2}\bar{X}^* - \phi^{1*}\right) < 0 \tag{8b}$$

and $dG^{2*}/d\alpha^2 > 0$ by Proposition 1(a). An increase in the laggard's arming reduces the leader's share of the contested pool (i.e., $\phi^1_{G^2} < 0$) while also reducing the size of that pool. Thus, the indirect payoff effect is negative, implying the direct and indirect effects push U^{1*} in opposite directions. Although it is unclear at this level of generality which effect dominates, we can resolve this issue as discussed shortly.

To study the dependence of the technology laggard's payoff U^{2*} on α^2, we similarly differentiate (2) for $i = 1$ with respect to α^2 but must account for the possibility that the laggard is resource constrained in its arming choice:

$$\frac{dU^{2*}}{d\alpha^2} = U^{2*}_{\alpha^2} + U^{2*}_{G^1}\left(\frac{dG^{1*}}{d\alpha^2}\right) + U^{2*}_{G^2}\left(\frac{dG^{2*}}{d\alpha^2}\right). \tag{9}$$

The first two terms in the RHS of (9) represent the direct and indirect effects of a change in α^2, along the lines discussed above for country 1, with

$$U^{2*}_{\alpha^2} = (1-\sigma)\,\phi^{2*} + \sigma > 0, \tag{10a}$$

$$U_{G^1}^{2*} = (1-\sigma)\left(\phi_{G^1}^{2*}\bar{X}^* - \phi^{2*}\right) < 0. \tag{10b}$$

Specifically, (10a) shows that an increase in α^2 has a positive direct effect on the laggard's payoff, while (10b) shows that the positive effect of an increase in α^2 on country 1's arming (established in Proposition 1(a)) has a negative impact. Additionally, when the laggard specializes completely in appropriation—namely, when $\alpha^2 \in (0, \alpha_0(\sigma))$ that implies $U_{G^2}^{2*} > 0$—we must also consider the indirect effect of adjustments in the laggard's own arming G^{2*} on U^{2*}, shown in the third term in (9). Since as established in Proposition 1(a) $dG^{2*}/d\alpha^2 > 0$ holds, this effect is positive and hence reinforces the direct payoff effect. Nonetheless, due to the presence of the negative indirect effect through the leader's adjustment in arming whether the laggard specializes in appropriation or not, the sign of the net effect of an increase in α^2 on the laggard's payoff remains unclear at this point. Once again, as we will see shortly, it is possible to sign the net effect.

How does the *ex-ante* degree of output security σ matter in this context? By partially differentiating the payoff functions (2) with respect to σ and evaluating the resulting expressions at the equilibrium of the arming subgame, one can obtain the direct payoff effects for each country i:

$$U_\sigma^{i*} = -\phi^{i*}\bar{X}^* + X^{i*} = (1-\phi^{i*})X^{i*} - \phi^{i*}X^{j*}, \quad i, j \in \{1,2\}, i \neq j. \tag{11}$$

Summing the expressions across $i = 1, 2$ shows that the aggregate direct payoff effect $U_\sigma^{1*} + U_\sigma^{2*}$ equals zero. Thus, given arming choices, as one country benefits from an increase in *ex-ante* security, the other country necessarily loses.

Let us focus on country 1. When both countries are unconstrained, they arm identically, $G^{i*} = \widetilde{G}$ as shown in Proposition 1(a), such that $\phi^{1*} = \phi^{2*} = \frac{1}{2}$. Thus, we have $U_\sigma^{1*} = \frac{1}{2}(\alpha^1 - \widetilde{G}) - \frac{1}{2}(\alpha^2 - \widetilde{G})$, which is strictly positive given $\alpha^1 > \alpha^2$. When country 2 is resource constrained so that $G^{2*} = \alpha^2$, we have $U_\sigma^{1*} = (1-\phi^{1*})(\alpha^1 - G^{1*})$, which is also positive since country 1 always diversifies its production ($G^{1*} < \alpha^1$). Accordingly, the direct effect of *ex-ante* security improvements ($\sigma \uparrow$) is positive for the technologically advanced country and negative for the laggard.[19] Of course, there are, in addition, indirect payoff effects due to adjustments in arming choices. From Proposition 1(b), we know that $dG^{i*}/d\sigma \leq 0$ for $i = 1, 2$, implying that the indirect effect of an increase in σ on both countries' payoffs is non-negative. Clearly, then, the technology leader will always find security improvements appealing. However, due to the negative direct effect, it is unclear how the laggard would view such improvements.[20]

We now argue that, despite the offsetting effects on equilibrium payoffs at work here, it

[19] In the limiting case where $\alpha^1 = \alpha^2$, the direct payoff effect is 0 for both countries.

[20] Note that the second indirect effect, analogous to the third term in (9) that arises when the laggard is resource constrained, vanishes because $dG^{2*}/d\sigma = 0$ in this case.

is possible to identify more precisely their dependence on the initial values of the laggard's technology α^2 and of the degree of output security σ. The next proposition explains.

Proposition 2 (Payoffs.) *Assuming imperfect output security ($\sigma < 1$), the equilibrium payoffs of the arming subgame can be characterized as follows*:

(a) *Improvements in the laggard's technology ($\alpha^2 \uparrow$) always increase its own payoff U^{2*}, but their effect on the leader's payoff U^{1*} depends on the initial value of α^2 relative to α^1 and on σ that jointly determine whether or not the laggard is resource constrained*:

  (i) *When the laggard is resource constrained, U^{1*} falls.*

  (ii) *When the laggard is not resource constrained, U^{1*} rises.*

(b) *Improvements in security ($\sigma \uparrow$) always enhance the leader's payoff U^{1*}. Their payoff effect for the laggard depends on α^2, given α^1, and the initial value of σ that jointly determine whether or not the laggard is resource constrained*:

  (i) *When the laggard is resource constrained, U^{2*} falls.*

  (ii) *When the laggard is not resource constrained, U^{2*} rises.*

Taking into account both the direct and indirect payoff effects that possibly move in opposite directions as described earlier, Proposition 2 clarifies the remaining ambiguities. First, the technology laggard always benefits from an improvement in its own dual-use technology ($\alpha^2 \uparrow$), whereas the leader benefits only if, given σ, the initial value of α^2 is sufficiently large to induce the laggard to produce both guns and butter (i.e., when $\alpha^2 \in [\alpha_0(\sigma), \alpha^1)$). By contrast, if the laggard specializes completely in predation (i.e., when $\alpha^2 \in (0, \alpha_0(\sigma))$), the leader is made worse off due to the dominance of the negative strategic effect. Specifically, the laggard applies the entire increase in its effective endowment (due to $\alpha^2 \uparrow$) to arming, implying its butter production remains unchanged at zero.[21] Second, while the leader always benefits from an improvement in *ex-ante* security ($\sigma \uparrow$), the laggard benefits only when it diversifies its production; otherwise, the direct negative effect of an increase in σ dominates to make the laggard worse off.

Fig. 1(c) depicts the dependence of both countries' payoffs on α^2 for $\sigma = 0$ and some $\sigma > 0$ as characterized in the proposition. This figure also shows the countries' payoffs under Nirvana U_n^i where $\sigma = 1$. As mentioned earlier, the leader's payoff in this special case U_n^1 is invariant to changes in α^2, whereas the laggard's Nirvana payoff U_n^2 is increasing in α^2. By

[21]As shown in Appendix A.2, the possible dominance of the adverse strategic payoff effect for the leader derives more generally from the tendency for the laggard to employ intensively its larger effective endowment in appropriative activities. This tendency increases as the initial distance between the countries' dual-use technologies rises, and more so as *ex-ante* security falls. Thus, while a binding resource constraint for the laggard is sufficient for the leader to find improvements in the laggard's dual-use technology unappealing, it is not necessary.

contrast, when peace is not certain (i.e., $\sigma < 1$), the leader's payoff falls with improvements in the laggard's technology provided the distance between their dual-use technologies is sufficiently pronounced, but rises otherwise. Thus, the possibility of conflict has sharply different implications for the payoff effects of increases in α^2 than those that follow from standard economic theory where peace is assumed to prevail. What's more, while the leader always prefers improvements in *ex-ante* security, the laggard need not.

3.3 Efficiency

Having discussed the effects of changes in the laggard's productivity on equilibrium arming and payoffs, we can now address the question of how these changes affect global efficiency. In the rent-seeking and conflict literatures, the cost of socially unproductive activities (an inverse measure of efficiency) is normally proxied by the aggregate quantity of guns produced. Applying this idea to the present setting, it is natural to argue that, insofar as technological progress amplifies the absorption of resources in appropriative/redistributive activities, it could hamper global efficiency. However, the impact of such progress on the total quantity of guns produced is just part of the story. Productivity improvements also directly affect the output of butter. To study the overall effect on efficiency, one must account for both effects.

We explore the above ideas, using a simple measure of efficiency—namely, the sum of the countries' payoffs: $\bar{U} \equiv U^1 + U^2$. From the definition of country i's payoff in (2) for countries $i = 1, 2$ and the fact that $\phi^1 + \phi^2 = 1$, one can see that

$$\bar{U} = \bar{X} = \alpha^1 - G^1 + \alpha^2 - G^2. \tag{12}$$

Recalling that $\bar{G} = G^1 + G^2$, we can write the change in equilibrium efficiency arising from an improvement in the laggard's dual-use technology as follows:

$$d\bar{U}^*/d\alpha^2 = 1 - d\bar{G}^*/d\alpha^2 \tag{13}$$

By Proposition 1(a), $d\bar{G}^*/d\alpha^2 > 0$ for initial values values of $\alpha^2 \in (0, \alpha^1)$. Thus, as shown in the expression above, a necessary condition for productivity improvements to enhance efficiency is that they do not raise aggregate arming by more than they raise the production of butter.

The next proposition shows precisely how improvements in the laggard's dual-use technology and in output security matter in this context.

Proposition 3 (Technology, security and efficiency.) *Assuming imperfect output security* ($\sigma < 1$), *improvements in the laggard's technology* ($\alpha^2 \uparrow$) *raise efficiency unless the laggard specializes in appropriation, in which case such improvements reduce efficiency. Further-*

more, improvements in ex-ante security ($\sigma \uparrow$) always enhance efficiency.

As this proposition establishes, improvements in the laggard's technology need not always enhance efficiency. The logic behind this finding, alluded to earlier, is simple and intuitive. In settings where the implementation of enforceable contracts on arming is not feasible—perhaps due to the absence of a supranational authority or weak laws and institutions—technological progress can induce a sufficiently large shift in the allocation of the countries' resources away from productive activities towards distributive conflicts, and in doing so create additional social costs that outweigh the social benefits driven by productivity gains for the laggard.[22] The proposition suggests that such an efficiency loss is more likely in situations where the laggard's technology (α^2) is further away from that of the leader (α^1) initially. Comparing Proposition 3 with Proposition 2 shows that the parameter space for which marginal improvements in the laggard's technology reduce global efficiency is precisely the same as the parameter space for which such improvements generate payoff losses for the leader—namely, when the resource constraint on the laggard's arming choice is constrained.

Since improvements in *ex ante* security reduce the parameter space for which the laggard is resource constrained, such improvements would naturally expand the space for which the two countries would jointly and individually benefit from technological progress for the laggard. However, while Proposition 3 establishes that security improvements always increase efficiency, Proposition 2(b.i) shows that the laggard is made worse off precisely when it is resource constrained. This sort of logic provides an economic rationale for the resistance of backward economies to economic reforms related to common security despite possible efficiency gains.

4 Technology Transfers

Having studied the effects of an exogenous advance in the laggard's dual-use technology on equilibrium arming, payoffs and efficiency in the second-stage subgame, we now turn to the first stage to study the endogenous determination of improvements in the laggard's technology through transfers from the leader. In particular, we seek to understand how the subgame perfect equilibrium of the extended game depends on the initial technological distance between countries, as well as on the *ex ante* degree of output security. To this end and as explained earlier, we suppose that technology-transfer decisions are made before arming choices. Each policymaker declares independently in a simultaneous-move stage

[22] One can show that, if countries differed instead only in their ability to transform their respective endowments into guns, then improvements in the laggard's military technology could induce it to devote less of its effective endowment to guns production and more to butter; nonetheless, they always lead to a greater aggregate allocation to guns and thus lower aggregate butter production, thereby reducing global efficiency. While the laggard unambiguously gains from improvements in its military technology, the leader always loses. (Details are available on request from the authors.)

game whether it accepts (A) or rejects (N) the transfer, taking into account how the transfer will affect arming decisions, the production of butter and its distribution. The transfer materializes (also in that stage) only if both countries choose A.

Following the literature on technology transfers, the analysis allows for the possibility that the laggard's ability to implement the state-of-the art technology is limited by its absorptive capacity (Keller, 2004). For example, there could be a loss in translating the blueprints of the superior technology and adjusting them for use by the laggard, similar to the "iceberg" metaphor of trade costs in the trade literature.[23] Let a^2 denote the dual-use technology that the laggard acquires if both countries agree to the transfer. A simple way to capture the laggard's possibly limited ability to absorb the technology is to suppose that $a^2 = \lambda\alpha^1$, where $\lambda \in (0, 1]$ is the effective rate of absorption. Obviously, $\lambda = 1$ identifies the case of a costless technology transfer. However, for a transfer to result in a technology upgrade for the laggard, the effective rate of transfer must be sufficiently large: $\lambda \in (\alpha^2/\alpha^1, 1]$.

Under the conditions of Proposition 2, we know that the laggard's equilibrium payoff U^{2*} is increasing in its technology α^2. Therefore, accepting a transfer to upgrade its technology (A) is a weakly dominant strategy for the laggard.[24] The leader's payoff is also increasing in α^2, but only when the resource constraint is not binding for the laggard's arming. When the laggard operates as a pure predator, the leader's payoff falls as α^2 rises. For ease of exposition, we discuss the implications with the help of Fig. 2 that depicts this relationship for $\sigma = 0$. As the figure highlights, there exist circumstances under which the leader would favor the transfer (A) and circumstances under which it would oppose it (N). Clearly, in this subgame, assuming the transfer results in an upgrade for the laggard, the leader's preferences over the transfer determine the equilibrium outcome. In particular, if the leader chooses N, then (N, N) is part of the subgame perfect equilibrium. And if the leader chooses A then (A, A) is the stage outcome.[25]

Turning to the subgame perfect equilibrium, observe from the figure that $\lim_{\alpha^2 \to 0} U^{1*} > \lim_{\alpha^2 \to \alpha^1} U^{1*}$ for $\sigma < 1$. The logic underlying this ranking is as follows. As α^2 approaches 0, both countries' arming becomes infinitesimal; at the same time, while laggard contributes nothing to the contested output in the second stage, its share of that output is also infinitesimal. Thus, as α^2 goes to zero, the leader can realize (approximately) its payoff under perfect security: $\lim_{\alpha^2 \to 0} U^{1*} = U^1_n$ $(= \alpha^1)$. At the other extreme as α^2 approaches α^1, the two countries produce identical quantities of guns $G^{i*} = \widetilde{G} = \frac{1}{2}\alpha^1 > 0$ for $i = 1, 2$ as shown

[23]Cohen and Levinthal (1989, 1990) provide an extended discussion of the cognitive and organizational aspects of absorptive capacity in the adoption of technology, underscoring the importance of in-house R&D.

[24]The dominance is "weak" for the laggard because its payoff from declaring either A or N is the same when the leader declares N. One can verify that this is also true for the leader.

[25]It should be noted that (N, N) is always part of a weakly dominated subgame perfect equilibrium.

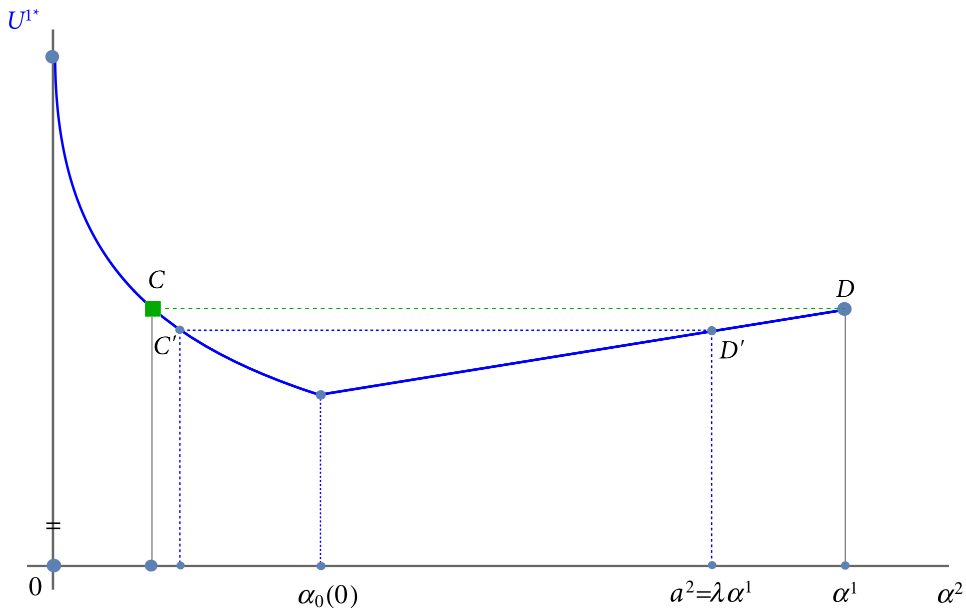

Figure 2: Payoff Effects of Transfers of Dual-Use Technology

in (5) with $\alpha_1 = \alpha_2$ and $\sigma = 0$, such that $\lim_{\alpha^2 \to \alpha^1} U^{1*} = \frac{1}{2}\alpha^1 < U_n^1$. These properties together with the ones established in Proposition 2 imply that the functional dependence of U^{1*} on α^2 is V-shaped, reaching the minimum where $\alpha^2 = \alpha_0(0)$.[26]

If $\lambda = 1$, the leader's payoff under the transfer is the one associated with point D, where $a^2 = \alpha^1$ in Fig. 2(a). The leader's payoff in the absence of a transfer depends on the initial value of α^2. For any value of α^2 less than the level associated with point C, the leader would refrain from offering the transfer. Why? Although the transfer would induce the laggard to contribute to the contested pool, it also causes the laggard to arm more aggressively in the contest over output. Because low values of α^2 (underdevelopment) constrain the laggard's ability to arm, refusing to make the transfer caps the laggard's power in the contest and generates a higher payoff for the leader. By contrast, for values of α^2 in the interval between points C and D, the leader favors a transfer.

Next, consider a value of $\lambda < 1$ that implies $a^2 = \lambda\alpha^1 \in (\alpha_0(\sigma), \alpha^1)$, as indicated by point D' in Fig. 2(a) when $\sigma = 0$. The laggard's limited absorptive capacity implies that, when α^2 is sufficiently large (i.e., associated with points to the right of D'), a transfer would be inconsequential. What about for smaller values of α^2? Once again, the leader would find the transfer unappealing if the value of α^2 is below the value associated with point C'. However, it would prefer to make the transfer if α^2 falls within the range associated points

[26] In the presence of complementary inputs, U^{1*} is U-shaped as illustrated in Appendix A.2.

C' and D'. Importantly, if $a^2 = \lambda\alpha^1 \leq \alpha_0(0)$ (or equivalently $\lambda \leq \frac{1}{3}$), then the set of initial α^2 values that render the transfer appealing to the leader would be empty.

Two salient findings emerge from the above analysis. First, countries that are at the low end of the technology ladder are more likely to find themselves locked in a "low-technology trap" or "underdevelopment" associated with dual-use technologies. The reason is that, by refusing to make the transfer to such rivals, the leader can contain their ability to arm, thereby securing a higher payoff for itself. Second, the more limited is the laggard's ability to absorb the state-of-the-art technology ($\lambda \downarrow$), the larger is the range of parameter values for which the laggard remains trapped in a low development state. Put differently, countries with lower absorptive capacity are more likely to be denied access to the superior technology, a sort of self-reinforcing phenomenon.

We can tease out the implications of improvements in *ex-ante* security ($\sigma \uparrow$) here with the help of Fig. 1(c), which shows that the leader's payoff (that continues to be V-shaped) rises at each value α^2, while the threshold value $\alpha_0(\sigma)$ associated with the kink in U^{1*} falls. For any given absorptive capacity λ, the horizontal line associated with the new payoff function rises to intersect it at the same value of $a^2 = \lambda\alpha^1$ (corresponding to point D' in Fig. 2), but the new horizontal line must intersect the new payoff function at a smaller value of α^2 (relative to that corresponding to point C' in Fig. 2). Thus, given any λ, greater *ex ante* output security ($\sigma \uparrow$) expands the range of α^2 values (given α^1) for which the leader will find a transfer appealing; at the same time, the range of initial α^2 values under which the laggard finds itself in a low-technology trap shrinks. Hence, countries at the low end of the technology ladder are less likely to be locked in a low-technology trap as σ increases.

We summarize our findings in the following proposition:

Proposition 4 (Low-technology traps.) *In the presence of imperfect security* ($\sigma < 1$) *with international differences in dual-use technologies, countries that are at the lowest end of the technology ladder are more likely to be locked in a low-technology trap. The range of parameter values for which a trap emerges expands with decreases in the laggards' absorptive capacity* ($\lambda \downarrow$) *and with decreases in the degree of output security* ($\sigma \downarrow$) *.*

To flesh out the policy implications of the emergence of such traps, observe first that global efficiency, $\bar{U}^* = U^{1*} + U^{2*}$, necessarily rises whenever both the leader and the laggard agree to implement a transfer. That leaves open the question of whether transfers could raise efficiency even when, given the laggard's capacity to absorb the leader's better technology and the *ex-ante* degree of output security, the laggard is trapped.

Recall from Proposition 3 that global efficiency declines with marginal improvements in the laggard's general-purpose technology ($\alpha^2 \uparrow$) when it is resource constrained in its arming choice. That is not to say, however, that discrete improvements in the laggard's technology via transfers necessarily reduce efficiency in such cases. As illustrated in Fig. 2, provided that α^2 is not too small relative to α^1, the leader is willing to make such transfers and global efficiency rises as a result even when the technology laggard is constrained initially. Furthermore, since the threshold value of α^2, below which the leader refuses to make a transfer, is decreasing in the laggard's absorptive capacity λ, efforts by the leader to increase λ could raise the leader's payoff and hence global efficiency. Nevertheless, since a trap remains even when $\lambda = 1$, such efforts, however extensive, cannot eliminate the trap for all laggards. What's more, these efforts are not costless, and the leader would have to balance the costs against the resulting (gross) payoff gains. Proposition 4 suggests an alternative approach to reduce the importance of technology traps and raise global efficiency—namely, by improving *ex-ante* security ($\sigma \uparrow$). But, while the range of α^2 values, given $\lambda \leq 1$, for which a trap emerges falls as σ increases, Proposition 2(b.i) suggests that the laggard could be made worse off. Accounting for the additional costs that would have to be borne by both countries to improve *ex-ante* security further diminishes the possible appeal of this alternative approach.

5 Empirical Analysis

In this section we test empirically the main predictions of our theory about the key determinants of technology transfer between leaders and laggards, including (i) output security/conflict, (ii) the technological distance between the rival leaders and laggards, and (iii) the absorption capacity of the laggard. To this end, Subsection 5.1 sets up the econometric model, and Subsection 5.2 presents our estimates and offers a discussion of our main findings along with the results from some robustness experiments.

5.1 Econometric Specification

With the predictions of our theory in mind and capitalizing on the developments in the gravity literature of trade (Larch et al., 2025) and cross-border patent flows (LaBelle et al., 2025), we specify the following econometric model:

$$\begin{aligned} \textit{TECH\_TRN}_{ij,t} = \exp\big\{ & \chi_{i,t} + \pi_{j,t} + \overrightarrow{\mu}_{ij} + \textit{POLICY}_{ij,t} \times \alpha + \beta_1 \textit{SANCTION}_{ij,t} \\ & + \beta_2 \textit{LDR\_LGD}_{ij,t} + \beta_3 (\textit{LDR\_LGD}_{ij,t} \times \textit{SANCTION}_{ij,t} \times \textit{TECH\_DIST}_{ij,t}) \\ & + \beta_4 (\textit{LDR\_LGD}_{ij,t} \times \textit{SANCTION}_{ij,t} \times \textit{CAPACITY}_{j,t}) \big\} \times \epsilon_{ij,t}, \end{aligned} \tag{14}$$

for all i, j, t. The dependent variable in equation (14), $\textit{TECH\_TRN}_{ij,t}$ which is intended to measure international technology transfers, denotes the total number of cross-border patents from source i to destination j at time t. These data are taken from the International Patent and Citations across Sectors (INPACT-S) database of LaBelle et al. (2025). Following that paper, our estimating sample covers all bilateral cross-border patent flows during the

1995–2018 period.[27]

To be sure, the theoretical analysis above has focused specifically on transfers of a dual-purpose technology, whereas the dependent variable in (14) does not distinguish between different types of technology. Nonetheless, our framework with some modifications could be used to study international differences in the technology for civilian goods production alone, again in the presence of imperfect output security, and the possibility of transfers of such technology. In contrast to our finding in this paper based on a dual-use technology though consistent with the findings of Skaperdas (1992) and Skaperdas and Syropoulos (1997) as well as Gonzales (2005), it is the technology laggard that tends to have a comparative advantage in arming and thus is more powerful. In this setting, advances in the laggard's technology to produce butter result in positive direct payoff effects for both countries; at the same time, however, they induce the laggard to arm by less and, moreover, induce the leader to arm by more leading to a positive indirect payoff effect for the leader and a negative indirect payoff effect for the laggard. The leader in this case would have an incentive to offer a transfer of its superior technology to the laggard, but the laggard would refuse such an offer if the negative indirect payoff effect is sufficiently large in magnitude. As shown in an earlier version of this paper (Camacho et al., 2022), this is more likely to happen under roughly the same conditions where the leader is less likely to offer the laggard a transfer of dual-use technology—namely, when the technological distance between the leader and laggard is sufficiently large and the laggard's absorptive capacity is relatively limited.

Guided by the trade gravity literature, we rely on the Poisson Pseudo Maximum Likelihood (PPML) estimator to obtain our main results. As demonstrated by Santos Silva and Tenreyro (2006), the PPML estimator has two main advantages for gravity regressions. First, the PPML estimator successfully addresses the issue of heteroskedasticity in trade flows data, which may also be a challenge in the current setting for cross-border patent flows. Second, due to its multiplicative form, the PPML estimator allows us to include the observations with zero bilateral patent flows. Another reason for using the Poisson estimator in our setting is that, unlike trade flows, cross-border patent flows is a count variable.[28]

The first four covariates on the RHS of (14) are standard in the gravity literature and,

[27] The INPACT-S database tracks cross-border patent flows across 91 patent authorities, 213 countries of origin, 40 years (1980-2019), and 31 ISIC Rev 3 2-digit codes. INPACT-S is more comprehensive than all other publicly available datasets along five key dimensions: (i) It encompasses a wider array of patent authorities, offering a full view of global patent activity; (ii) It provides industry-specific bilateral data, allowing to perform sectoral analysis; (iii) It captures a greater number of patent applications through imputation methods; (iv) It includes comprehensive data on cross-country and cross-sector citation data; and (v) It includes consistently constructed data on cross-border and domestic patents. We refer the reader to LaBelle et al. (2025) for further details on this database.

[28] We refer the reader to Santos Silva and Tenreyro (2021) and Larch et al. (2025) for summaries and discussions of the benefits of using the PPML estimator for gravity regressions.

to motivate them, we rely on LaBelle et al. (2025) who derive a gravity equation for cross-border patents. The first three of these are fixed effects. $\chi_{i,t}$ denotes a full set of source-time fixed effects, which control for and absorb any source-time-specific characteristics (e.g., the level of technology, prices, institutional quality, national regulations, taxes, etc.) that may impact technology transfers. Similarly, $\pi_{j,t}$ denotes the set of destination-time fixed effects, which control for any destination-time-specific characteristics that may impact patent flows. $\overrightarrow{\mu}_{ij}$ denotes directional country-pair fixed effects, which fully control for any time-invariant asymmetric technology-transfer frictions between the source and the destination.[29]

The next term in (14), $POLICY_{ij,t}$, is a vector that includes several policy variables, which have been shown (e.g., by LaBelle et al. (2025) to affect cross-border patent flows. In particular, we use an indicator variable for regional trade agreements, $RTA_{ij,t}$, that takes a value of one if countries i and j have an RTA in force at time t. Following Martínez and Chelala (2021), we distinguish between RTAs with and without technology provisions (respectively, $RTA\_TECH_{ij,t}$ vs. $RTA\_NO\_TECH_{ij,t}$). In addition to RTAs, we include indicators for membership in the Trade-Related Aspects of Intellectual Property Rights (TRIPS) agreement and the Patent Cooperation Treaty (PCT) (respectively, $TRIPS_{ij,t}$ and $PCT_{ij,t}$). The data on all policy variables come from LaBelle et al. (2025).

The next four terms in (14) are motivated by our theory and, therefore, are new to the literature. First, we introduce an indicator variable for sanctions ($SANCTION_{ij,t}$) as a proxy for potential conflict that is central to our theory.[30] Specifically, it is the anticipation of a possible dispute that induces each country to arm in preparation to influence the outcome should a dispute arise; as shown in the theory, each country's incentive to devote resources to arming and forego butter production depends on the dual-use technologies available to both countries. The indicator variable $SANCTION_{ij,t}$ also has some appeal from an econometric perspective, since our estimation sample includes a relatively large number of country-pair observations where at least one sanction was in place, allowing us to identify more precisely the key interactions, which are also conditional on transfers from leaders to laggards.[31] Finally, we are not aware of existing studies that estimate the impact of sanctions on cross-border patent flows. While our theory yields no predictions regarding

[29] Baier and Bergstrand (2007) demonstrate that the country-pair fixed effects mitigate potential endogeneity concerns with bilateral policies in gravity models. Such a concern applies to "sanctions," which we use to proxy conflict in our setting as discussed below.

[30] Consistent with our theory, we use an indicator for the presence of any sanction in the main analysis. In our robustness analysis, we experiment with an indicator for "trade sanctions" and also with a count variable for the number of different types of sanctions in place. The data on sanctions are from the Global Sanctions Database (GSDB) of Felbermayr et al. (2020) and Syropoulos et al. (2024).

[31] For comparison, we also experimented with an indicator for the presence of strategic rivalries (based on Thompson et al., 2020), which gave us only 75 non-zero observations to identify the effects of the covariates of interest; militarized interstate disputes from the Correlates of War database gave even fewer non-zero observations (i.e., less than 30).

the overall impact, it does have implications for how the presence of conflict conditions the influence of the technological distance between the leader and the laggard and the absorptive capacity of the laggard. We introduce these interactions below.

Second, we introduce a binary variable, $LDR\_LGD_{ij,t}$, that takes on the value of 1 for patent flows from the leader i to the laggard j and 0 otherwise. Although our theory does not yield any predictions about the overall impact of this indicator either, it too has implications for the key interactions as described shortly. We experiment with several ways to distinguish between technology leaders and laggards. To obtain our main results, we define as leaders as those countries that are in the upper half (top 50th percentile) of the distribution of patents in the world, whereas laggards are the countries in the bottom half of the patent distribution. In the robustness analysis, we use a more conservative definition of $LDR\_LGD_{ij,t}$, where the leaders are defined as those above the 75th percentile and the laggards are below the 25th percentile of the distribution of patents in the world. We also experiment with two alternative definitions of the leaders: (i) based only on domestic patents and (ii) based on the top ten inventors in the world.

The next two terms in (14) allow us to estimate the key interactions. The first of these, $LDR\_LGRD_{ij,t} \times SANCTION_{ij,t} \times TECH\_DIST_{ij,t}$, is defined as an interaction between the indicator variable $LDR\_LGD_{ij,t}$, the dummy variable for sanctions ($SANCTION_{ij,t}$), and a continuous variable "technological distance," $TECH\_DIST_{ij,t}$ measured by the logarithm of the difference between the number of patents in leader i and laggard j at time t. This interaction is crucial for our analysis because it allows to test one of the key predictions of our theory—namely, the inverse relationship between technological distance and technology transfers from leaders to laggards who are potentially involved in a conflict that motivates them to arm. Accordingly, we expect that the estimate of the coefficient on this term, β_3, will be negative.

The second interaction term, $LDR\_LGD_{ij,t} \times SANCTION_{ij,t} \times CAPACITY_{j,t}$, allows us to test the prediction of our theory that, conditional on the presence of potential conflict between the leader and the laggard, if the laggard's capacity to absorb technologies is sufficiently limited, a proposed technology transfer is likely to be blocked. This variable is defined as an interaction between the indicator variable $LDR\_LGD_{ij,t}$, the dummy variable for sanctions ($SANCTION_{ij,t}$), and a continuous "capacity" variable, $CAPACITY_{j,t}$, which is defined as the logarithm of number of patents in laggard j at time t. Our assumption is that a larger number of patents reflects a larger absorptive capacity and, based on our theory, we expect the estimate of the coefficient on this variable, β_4, to be positive. That is to say, a larger capacity for the laggard j should be associated with more technology transfers to this country.

Finally, following the standard approach in the gravity literature, in our main specifications we cluster the standard errors by country pair. However, our conclusions remain robust to using three-way clustering, i.e., by source, destination, and time.

5.2 Estimation Results and Analysis

To highlight the importance of the new theory-motivated terms in our model and especially the interactions among them, we develop the empirical analysis sequentially. Our main results are reported in Table 1. The benchmark results reported in column (1) exclude the variables from our theory. Without going into detail, we note that, overall, the estimates are as expected. Specifically, we find that RTAs and TRIPS promote technology transfer; similarly, the estimated impact of PCT positive, though not statistically significant. LaBelle et al. (2025) find that the impact of PCT is heterogeneous depending on the level of development, thereby offering a possible explanation for this last result.

Table 1: Gravity estimates for technology transfers

	(1) Benchmark	(2) Conflict	(3) Leader/Laggard	(4) TechDist	(5) Capacity
$RTA\_TECH_{ij,t}$	0.061	0.059	0.059	0.059	0.060
	$(0.032)^{+}$	$(0.032)^{+}$	$(0.032)^{+}$	$(0.032)^{+}$	$(0.032)^{+}$
$RTA\_NO\_TECH_{ij,t}$	0.599	0.597	0.597	0.597	0.602
	$(0.143)^{**}$	$(0.143)^{**}$	$(0.143)^{**}$	$(0.143)^{**}$	$(0.143)^{**}$
$TRIPS_{ij,t}$	0.372	0.367	0.367	0.368	0.366
	$(0.092)^{**}$	$(0.090)^{**}$	$(0.090)^{**}$	$(0.090)^{**}$	$(0.090)^{**}$
$PCT_{ij,t}$	0.020	0.019	0.016	0.014	0.011
	(0.103)	(0.103)	(0.103)	(0.103)	(0.102)
$SANCTION_{ij,t}$		-0.028	-0.028	-0.027	-0.029
		(0.034)	(0.034)	(0.034)	(0.034)
$LDR\_LGD_{ij,t}$			-0.276	-0.268	-0.289
			$(0.146)^{+}$	$(0.146)^{+}$	$(0.146)^{*}$
$LDR\_LGD_{ij,t} \times SANCTION_{ij,t} \times TECH\_DIST_{ij,t}$				-0.012	-0.096
				$(0.007)^{+}$	$(0.018)^{**}$
$LDR\_LGD_{ij,t} \times SANCTION_{ij,t} \times CAPACITY_{j,t}$					0.232
					$(0.045)^{**}$
N	62176	62176	62176	62176	62176

Notes: This table reports estimates of the effects of the determinants of technology transfers/cross-border patents over our sample, 1995–2018. All estimates are obtained from specification (14). The dependent variable in each specification is the number of cross-border patents and the estimator is always PPML. The results in column (1) are obtained with standard policy variables. Column (2) introduces an indicator variable for conflict/sanctions. Column (3) adds a dummy variable for transfers from leaders to laggards. Column (4) adds an interaction between the indicator variable for leaders vs. laggards, the variable for sanctions, and the technological distance between the leaders and the laggards. Finally, column (5) adds an interaction between the variable for sanctions and the technological capacity of the laggards. Standard errors, shown in parentheses, are clustered by country pair. $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. See the text for further details.

Column (2) of Table 1 introduces the dummy variable for sanctions, $SANCTION_{ij,t}$. The estimated coefficient on this indicator suggests a negative impact of conflict on technology transfers; however, it is small in magnitude and not statistically significant. The implication is that the presence of sanctions is not a key determinant of cross-border patent flows on average. In column (3) of Table 1, we add the indicator variable for technology transfers from leaders to laggards, $LDR\_LGD_{ij,t}$. The estimated coefficient on this indicator is negative and marginally significant, suggesting that the number of bilateral transfers from leaders to laggards tends to be small relative to the number of all other technology transfers (i.e., within the group of leaders, within the group of laggards and finally from laggards to leaders).

As noted earlier, our theory does not predict the overall impact of $SANCTION_{ij,t}$ or $LDR\_LGD_{ij,t}$ on technology transfers. But, we now turn to consider the impact of these indicators through the lens of our theory, where conflict plays a central role. Column (4) of Table 1 tests our prediction for an inverse relationship between technological distance and technology transfer between leaders and laggards who are in conflict, by introducing the variable $LDR\_LGD_{ij,t} \times SANCTION_{ij,t} \times TECH\_DIST_{ij,t}$, which, as defined earlier, is an interaction between the indicator variable for transfers from leaders to laggards, the dummy variable for sanctions, and the logarithm of the difference between the number of patents in leader i and laggard j at time t. As predicted by our theory, the estimate of the coefficient on the new interaction is negative, and it is statistically significant, suggesting that larger technological gaps between the leader and the laggard who are in conflict lead to less technology transfers.

The results in Column (5) are obtained after adding a variable that measures the technological capacity of the laggard: $LDR\_LGD_{ij,t} \times SANCTION_{ij,t} \times CAPACITY_{j,t}$, which is defined as the interaction between the indicator variable for transfers from leaders to laggards, the dummy variable for sanctions, and our measure of the laggard's technology absorptive capacity. Consistent with out theory, the estimate on the new variable is positive, and it is statistically significant, suggesting that when the laggard's capacity to absorb the more advanced technology is greater, more technology transfers to it will be made.

We conclude the empirical analysis with several robustness checks, which are presented in Tables 2 and 3. To ease comparisons, Column (1) of both tables replicates the results from the last column from Table 1. In Table 2, Column (2) reproduces the results from column (1) but with the OLS estimator. Column (3) uses trade sanctions, instead of sanctions more generally, as a proxy for potential conflict. Both Columns (4) and (5) make use of an alternative proxy for conflict one that arguably provides some indication of the severity of conflict. In particular, the variable $SANCTION\_INT_{ij,t}$ is defined as count of different types of sanctions in place imposed on country i or j by the other country $j \neq i$ in time t, which can take on a value of 0 to 6. In Column (4), it is interacted with the $LDR\_LGD_{ij,t}$ indicator in place of the original interactive term for the technological distance between the leader and the laggard used in Column (1); in Column (5), it is used to construct the interactive terms for the technological distance and the laggard's absorptive capacity. Although the magnitudes of the estimates of the key coefficients differ, the results are consistent with those shown in Column (1).

Table 2: Robustness analysis

	(1) Main	(2) OLS	(3) Trade	(4) Intensity-I	(5) Intensity-II
$RTA\_TECH_{ij,t}$	0.060	-0.030	0.060	0.059	0.060
	$(0.032)^{+}$	(0.031)	$(0.032)^{+}$	$(0.032)^{+}$	$(0.032)^{+}$
$RTA\_NO\_TECH_{ij,t}$	0.602	0.492	0.604	0.598	0.604
	$(0.143)^{**}$	$(0.056)^{**}$	$(0.142)^{**}$	$(0.143)^{**}$	$(0.143)^{**}$
$TRIPS_{ij,t}$	0.366	0.218	0.371	0.367	0.367
	$(0.090)^{**}$	$(0.050)^{**}$	$(0.090)^{**}$	$(0.090)^{**}$	$(0.090)^{**}$
$PCT_{ij,t}$	0.011	0.317	0.022	0.015	0.014
	(0.102)	$(0.070)^{**}$	(0.103)	(0.103)	(0.102)
$SANCTION_{ij,t}$	-0.029	0.037		-0.028	-0.028
	(0.034)	(0.040)		(0.034)	(0.034)
$LDR\_LGD_{ij,t}$	-0.289	-0.480	-0.271	-0.269	-0.277
	$(0.146)^{*}$	$(0.107)^{**}$	$(0.144)^{+}$	$(0.145)^{+}$	$(1.44)^{+}$
$LDR\_LGD_{ij,t} \times SANCTION_{ij,t} \times TECH\_DIST_{ij,t}$	-0.096	-0.093			
	$(0.062)^{*}$	$(0.015)^{**}$			
$LDR\_LGD_{ij,t} \times SANCTION_{ij,t} \times CAPACITY_{j,t}$	0.232	0.185		0.146	
	$(0.045)^{**}$	$(0.035)^{**}$		$(0.062)^{*}$	
$TRADE\_SANCT_{ij,t}$			-0.036		
			(0.029)		
$LDR\_LGD_{ij,t} \times TRADE\_SANCT_{ij,t} \times TECH\_DIST_{ij,t}$			-0.097		
			$(0.022)^{**}$		
$LDR\_LGD_{ij,t} \times TRADE\_SANCT_{ij,t} \times CAPACITY_{j,t}$			0.157		
			$(0.053)^{**}$		
$LDR\_LGD_{ij,t} \times SANCTION\_INT_{ij,t}$				-0.465	
				$(0.185)^{*}$	
$LDR\_LGD_{ij,t} \times SANCTION\_INT_{ij,t} \times TECH\_DIST_{ij,t}$					-0.038
					$(0.007)^{**}$
$LDR\_LGD_{ij,t} \times SANCTION\_INT_{ij,t} \times CAPACITY_{j,t}$					0.084
					$(0.017)^{**}$
N	62176	52660	62176	62176	62176
R^2		0.925			

Notes: This table reports estimates from a series of experiments that test and confirm the main findings from Table 1. Column (1) reproduces the main estimates from column (5) of Table 1. Column (2) replicates the results from column (1) but with the OLS estimator. Column (3) uses trade sanctions as a proxy for conflict. Column (4) uses the number of different types of sanctions for the conflict proxy when interacted with the $LDR\_LGD_{ij,t}$ dummy variable. Column (5) uses this intensity measure of sanctions in the interaction terms for technological distance and the laggard's absorptive capacity. Standard errors, shown in parentheses, are clustered by country pair. $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. See the text for further details.

The robustness analysis in Table 3 considers alternative approaches to distinguish between technological leaders and laggards. In column (2), we introduce a more conservative threshold, which defines leaders as the countries that fall above the 75th percentile in the distribution of patents in the world and laggards as those that fall below the 25th percentile in the same distribution ($LDR\_LGD\_C_{ij,t}$). The results in column (3) are obtained with a definition of leaders based on the number of domestic (as opposed to all, domestic plus international) patents ($LDR\_LGD\_D_{ij,t}$). Finally, the estimates in the last column of Table 3 define leaders as the top 10 patent inventors in our sample, which include the United States, Japan, China, Germany, Korea, the United Kingdom, Taiwan, Australia, Canada, and France ($LDR\_LGD\_T_{ij,t}$). With the exception of column (2), where the estimate of the impact of the laggard's absorptive capacity is not statistically significant (but still positive),

Table 3: Additional robustness analysis

	(1) Main	(2) Conserv.	(3) Domestic	(4) Top
$RTA\_TECH_{ij,t}$	0.060	0.059	0.060	0.060
	$(0.032)^{+}$	$(0.032)^{+}$	$(0.032)^{+}$	$(0.032)^{+}$
$RTA\_NO\_TECH_{ij,t}$	0.602	0.597	0.600	0.599
	$(0.143)^{**}$	$(0.143)^{**}$	$(0.143)^{**}$	$(0.143)^{**}$
$TRIPS_{ij,t}$	0.366	0.367	0.367	0.367
	$(0.090)^{**}$	$(0.090)^{**}$	$(0.090)^{**}$	$(0.090)^{**}$
$PCT_{ij,t}$	0.011	0.018	0.015	0.017
	(0.102)	(0.103)	(0.102)	(0.102)
$SANCTIONS_{ij,t}$	-0.029	-0.028	-0.029	-0.029
	(0.034)	(0.034)	(0.034)	(0.034)
$LDR\_LGD_{ij,t}$	-0.289			
	$(0.146)^{*}$			
$LDR\_LGD_{ij,t} \times SANCTION_{ij,t} \times TECH\_DIST_{ij,t}$	-0.096			
	$(0.018)^{**}$			
$LDR\_LGD_{ij,t} \times SANCTION_{ij,t} \times CAPACITY_{j,t}$	0.232			
	$(0.045)^{**}$			
$LDR\_LGD\_C_{ij,t}$		-0.464		
		$(0.108)^{**}$		
$LDR\_LGD\_C_{ij,t} \times SANCTION_{ij,t} \times TECH\_DIST_{ij,t}$		-0.050		
		$(0.026)^{+}$		
$LDR\_LGD\_C_{ij,t} \times SANCTION_{ij,t} \times CAPACITY_{j,t}$		0.173		
		(0.106)		
$LDR\_LGD\_D_{ij,t}$			-0.253	
			$(0.066)^{**}$	
$LDR\_LGD\_D_{ij,t} \times SANCTION_{ij,t} \times TECH\_DIST_{ij,t}$			-0.064	
			$(0.015)^{**}$	
$LDR\_LGD\_D_{ij,t} \times SANCTION_{ij,t} \times CAPACITY_{j,t}$			0.225	
			$(0.053)^{**}$	
$LDR\_LGD\_T_{ij,t}$				-0.196
				$(0.056)^{**}$
$LDR\_LGD\_T_{ij,t} \times SANCTION_{ij,t} \times TECH\_DIST_{ij,t}$				-0.027
				$(0.011)^{*}$
$LDR\_LGD\_T_{ij,t} \times SANCTION_{ij,t} \times CAPACITY_{j,t}$				0.066
				$(0.029)^{*}$
N	62176	62176	62176	62176

Notes: This table reports estimates from a series of additional experiments based on alternative approaches to distinguish between technology leaders and technology laggards. Column (1) reproduces the main estimates from column (5) of Table 1. Column (2), uses a more conservative definition of the dummy variable, where the leaders are defined above the 75th percentile and the laggards below the 25th percentile, respectively, of the distribution of patents in the world ($LDR\_LGD\_C_{ij,t}$). Column (3) defines $LDR\_LGD\_D_{ij,t}$ based only on domestic patents. Finally, column (4) defines $LDR\_LGD\_T_{ij,t}$ based on the top 10 inventors in the world. Standard errors, shown in parentheses, are clustered by country pair. $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$. See the text for further details.

all estimates from these robustness experiments are consistent with our main findings.

Overall, we conclude that the analysis in this section offers empirical support for the key theoretical predictions about the relationships between technology transfer and (i) conflict between the laggards and leaders, (ii) the technological distance between the leaders and the laggards and (ii) the absorption capacity of the laggard.

6 Concluding Remarks

While it is widely believed that productivity improvements through technology transfers represent a major driver of world economic growth, sanctions recently imposed by the US against the technology sectors of China and Russia, particularly those that can support the respective countries' military strength, point to the possibility that countries might seek to limit such improvements. This paper develops a one-period, guns-versus-butter model in which output insecurity—one sort of geopolitical friction—is the source of inefficiency. It is this inefficiency that can render a transfer of the dual-purpose technology undesirable to the technology leader. To be more precise, our simple setting nests the striking benchmark case where conflict is not possible and thus output is perfectly secure, such that countries would not arm, and technology transfers would never be blocked. The possibility of conflict motivates arming that depends on the technology held by both countries. Hence, technology transfers generate not only a positive direct payoff effect, but also possibly an adverse strategic effect through arming incentives.

Our characterization of the total payoff effects for both countries shows that a transfer always benefits the laggard but not necessarily the leader. When the technological distance is large initially and the *ex-ante* degree of output security is sufficiently low, advances in the laggard's technology induce it to build up its military strength. The resulting adverse strategic effect for the leader swamps the positive direct effect and thus reduces its payoff.[32] These findings point to the possible emergence of a low-development or low-technology trap, wherein a sufficiently low initial level of technology for the laggard relative to the leader makes it more likely that a transfer would be blocked by the leader.

Consistent with the theory, our empirical analysis provides evidence that technology transfers from leaders to laggards who are potentially involved in conflict, proxied by the presence of sanctions, are on average lower when technological distance between them is larger and when the laggard's ability to absorb the new technology is lower. Our findings, which remain intact with alternative proxies of conflict and different ways of distinguishing between technology leaders and laggards, complement existing empirical analyses of cross-border patent flows that abstract from geopolitical frictions altogether.

[32] As noted earlier and discussed in Appendix A.2, although specialization in predation by the laggard is sufficient for this result, it is not necessary. In particular, when there are diminishing returns in the production of butter with respect to human capital, each country diversifies in its production of butter and guns. Nonetheless, the laggard tends to employ intensively any improvement in its dual-use technology in the production of guns, thereby generating a relatively large negative strategic payoff effect for the leader. Interestingly, if the degree of diminishing returns is sufficiently strong, the leader's payoff could be decreasing in all α^2 values, not just small ones. (For more details see Online Appendix B.)

One possible extension of the theoretical analysis involves allowing for an asymmetric distribution of resource endowments (i.e., $R^1 \neq R^2$). It turns out that such an extension yields comparable results. There are, however, two notable exceptions. First, when the laggard's resource endowment is sufficiently small relative to that of the leader (more precisely, when $R^2/R^1 < (1-\sigma)/(3+\sigma)$) such that it would be resource constrained even were it to have full access to the leader's superior technology (i.e., $\alpha^2 = \alpha^1$), the leader has no incentive to offer a technology transfer for any value of $\alpha^2 \in (0, \alpha^1)$. Second, when the laggard's resource endowment is sufficiently large relative to that of the leader (more precisely, when $R^2/R^1 > 3$) such that the leader would be resource constrained in its arming choice in the limiting case where $\alpha^2 = \alpha^1$ and the laggard could perfectly implement that superior technology ($\lambda = 1$), the leader necessarily offers a technology transfer, and the laggard gladly accepts that.[33] Within this slightly extended framework one can study the possible value of *ex ante* resource transfers. For example, in the first extreme case where R^2 is relatively small, the leader would clearly accept such a transfer from the laggard but that would not induce it to offer the laggard a technology transfer in exchange. Thus, the laggard has no incentive to offer a resource transfer, though it would improve efficiency. Nonetheless, in this extreme case, the leader might be willing to offer a resource transfer to the laggard and a technology transfer along with it, both of which the laggard would happily accept.

The analysis could be extended in a number of other potentially fruitful directions. Consider, for example, an extension with an additional country—say, the rest of the world (ROW)—that is not directly involved in the conflict but might have an interest in promoting the diffusion of the leader's superior technology towards the laggard or perhaps a broader interest in limiting conflict between the two adversaries. Alternatively, ROW might be allied with one of the two adversaries. One could ask, depending on ROW's objectives and constraints, how might ROW intervene and what effects its intervention would have. Of course, the answer would also depend on the structure of technology across the three countries. But, with the appropriate modifications, the model could be used to understand why a third (friendly) country might provide assistance to one of the adversaries and the form that this assistance takes—for example, a transfer of resources or technology.

One could also extend the model to consider the importance of international trade (e.g., in intermediate inputs) between the two adversaries. Two distinct questions emerge in such contexts. First, for any given difference in technologies, does trade benefit both sides? In standard settings—where, there is typically no arming or arms are kept fixed at predefined levels—the answer to this question is a resounding yes. Because arming is endogenous in our setting, however, this answer could be incorrect. Indeed, Garfinkel et al. (2022) have

[33] Details are available from the authors on request.

shown that, when countries trade before they arm and, thus, can direct their (income) gains from trade into productive and predatory investments, sufficiently affluent countries find trade unappealing. The finding is driven by the tendency of relatively poorer countries to channel more of their relatively larger gains from trade into arming as compared with their rivals. But trade (and possibly trade agreements) could take place after countries have made their arming decisions. This alternative timing of trade relative to arming choices raises a host of new possibilities. Our preliminary analysis of such a setting reveals that the possibility of trade (in the event no conflict) raises the marginal cost of arming for all countries, but by less for technologically advanced countries. As a consequence, these countries may pursue their security interests more aggressively than their lagging rivals, thus raising the possibility that economic interdependence is disadvantageous to technologically backward countries. In sum, the sequence of countries' arming and trading decisions and the way the gains from trade influence arming decisions—which are especially relevant in dynamic environments—matter.

The second question is this: How does trade that occurs after countries have armed affect their attitudes toward technology transfers? Perhaps unsurprisingly, our preliminary analysis suggests that—in addition to the degree of insecurity, the type of technology considered, and the technological distance between countries—the magnitude of their gains from trade plays a prominent role in this context. Interestingly, provided the gains from from trade are sufficiently large, trade can enhance the appeal of technology transfers to both sides. We plan to pursue these questions more rigorously in future research.

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A Appendix

This appendix presents proofs of the propositions in the main text. It also substantiates our claim that complete specialization by the laggard in arming and appropriation is a sufficient but not a necessary condition for the leader to find dual-use (or general-purpose) technology transfers unappealing.

A.1 Proofs of the propositions

For the proofs of Propositions 1 and 2 to follow, we study the effects of changes in $\theta \in \{\alpha^2, \sigma\}$, distinguishing between the two cases depending on whether the laggard ($i = 2$) is resource constrained in its arming choice and thus specializes in appropriation or not. This partition of the parameter space is determined by the value of α^2 in relation to the threshold derived in the main text, $\alpha_0(\sigma) \equiv \frac{1-\sigma}{3+\sigma}\alpha^1$ for $\sigma \in [0, 1)$:

***Case* 1:** If $\alpha^2 \in (0, \alpha_0(\sigma))$, the laggard country ($i = 2$) is resource constrained, in which case $G^{2*} = \alpha^2$ and $G^{1*} = B^1(\alpha^2) = -\alpha^2 + \sqrt{(1-\sigma)\,\alpha^2\,(\alpha^1 + \alpha^2)}$.

***Case* 2:** If $\alpha^2 \in [\alpha_0(\sigma), \alpha^1]$, neither country is resource constrained. Then, $G^{1*} = G^{2*} = \widetilde{G}\left(\alpha^2, \sigma\right) = \frac{1}{4}\,(1-\sigma)\left(\alpha^1 + \alpha^2\right)$.

Proof of Proposition 1. Let us define $m^2 \equiv \frac{\alpha^2}{\alpha^1+\alpha^2}$, and note that $\alpha^2 < \alpha_0(\sigma)$ implies $m^2 < \frac{1}{4}(1-\sigma)$. With that relationship and recalling that $\alpha_0'(\sigma) < 0$ where $\alpha_0\,(0) = \alpha^1/3$ and $\alpha_0\,(1) = 0$, we proceed to consider the two cases just described:

<u>*Case* 1, $\theta = \alpha^2$</u>: Using the definition of m^2, we can rewrite G^{1*} shown in this case as

$$G^{1*} = \alpha^2 \left(-1 + \sqrt{\frac{1-\sigma}{m^2}}\right). \tag{A.1}$$

When combined with the arming solution for country 2 ($G^{2*} = \alpha^2$), (A.1) implies

$$\frac{G^{1*}}{G^{2*}} = -1 + \sqrt{\frac{1-\sigma}{m^2}} > 1, \tag{A.2}$$

where the inequality follows from the requirement in this case, $\alpha^2 < \alpha_0(\sigma)$, that implies $m^2 < \frac{1}{4}(1-\sigma)$. Thus, by the conflict technology in (1), the leader is the more powerful country when the laggard specializes in appropriation.

Next, we differentiate the expression for G^{1*} in (A.1) with respect to α^2, while taking into account the definition of $m^2 \equiv \frac{\alpha^2}{\alpha^1+\alpha^2}$, to obtain

$$\frac{dG^{1*}}{d\alpha^2} = -1 + \frac{1+m^2}{2}\sqrt{\frac{1-\sigma}{m^2}}. \tag{A.3}$$

One can verify that $d^2G^{1*}/(d\alpha^2)^2 < 0$, such that $dG^{1*}/d\alpha^2$ attains a minimum at $\alpha^2 = \alpha_0$. Since $dG^{1*}/d\alpha^2|_{\alpha^2=\alpha_0(\sigma)} = \frac{1}{4}(1-\sigma) > 0$, $dG^{1*}/d\alpha^2 > 0$ holds for all $\alpha^2 \in (0, \alpha_0(\sigma)]$. Furthermore, it follows from (A.2) that, since m^2 is increasing in α^2, G^{1*}/G^{2*} is decreasing in α^2. It then follows from (1) that the leader's power ϕ^{1*} is also decreasing in α^2.

Case 2, $\theta = \alpha^2$: In this case, the two countries arm identically $G^{1*} = G^{2*} = \widetilde{G}$, meaning that they share power equally. In addition, from the solution for $\widetilde{G}$ shown above in this case, we have $dG^{1*}/d\alpha^2 = dG^{2*}/d\alpha^2 = d\widetilde{G}/d\alpha^2 = \frac{1}{4}(1-\sigma) > 0$, such that increases in α^2 induce more arming, while leaving the balance of power unchanged, as needed.

Cases 1 and 2, $\theta = \sigma$: Finally, we characterize the dependence of G^{i*} on σ in the two cases. In case 1, where G^{1*} satisfies (A.1) and $G^{2*} = \alpha^2$, it follows immediately that $dG^{1*}/d\sigma < 0$ and $dG^{2*}/d\sigma = 0$, which imply from (1) that increases in σ erode the leader's power advantage. In case 2, because $G^{1*} = G^{2*} = \widetilde{G}$ shown in (5), we have $dG^{i*}/d\sigma = d\widetilde{G}/d\sigma = -\frac{1}{4}(\alpha^1 + \alpha^2) < 0$ for $i = 1, 2$, implying less arming by both countries with no change in the balance of power and thereby completing the proof. ||

Proof of Proposition 2. Again, distinguishing between cases 1 and 2, we now use equations (7) and (9) to calculate the total payoff effects of an increase in $\theta \in \{\alpha^2, \sigma\}$ for the leader ($i = 1$) and laggard ($i = 2$) respectively.

Case 1, $\theta = \alpha^2$: Starting with the resource-constrained country (i.e., the technology laggard, $i = 2$), we proceed to fill in the three components of (9). The first term, $U^{2*}_{\alpha^2} > 0$, is shown in (10a). Turning to the second term, we can use (10b) with our assumptions that imply $\bar{X}^* = X^{1*} + X^{2*} = X^{1*} = (\alpha^1 - G^{1*})$ and the specification for conflict in (1) that implies $\phi^2_{G^1} = -\phi^1\phi^2/G^1$ to find:

$$U^{2*}_{G^1}\frac{dG^{1*}}{d\alpha^2} = -\left[(1-\sigma)\,\phi^{1*}\phi^{2*}\left(\frac{\alpha^1 - G^{1*}}{G^{1*}}\right) + (1-\sigma)\,\phi^{2*}\right]\frac{dG^{1*}}{d\alpha^2} \tag{A.4a}$$

Next, we use (3) for $i = 2$. With the conflict technology in (1) that implies $\phi^2_{G^2} = \phi^1\phi^2/G^2$, we can to identify the indirect payoff effect that arises as the (resource-constrained) laggard adjusts its own guns according to $dG^{2*}/d\alpha^2 = 1$:

$$U^{2*}_{G^2}\frac{dG^{2*}}{d\alpha^2} = (1-\sigma)\,\phi^{1*}\phi^{2*}\left(\frac{\alpha^1 - G^{1*}}{\alpha^2}\right) - \left[\sigma + (1-\sigma)\,\phi^{2*}\right]. \tag{A.4b}$$

Since the leader is not resource constrained, $U^{1*}_{G^1} = 0$ always holds. Thus, equation (3) for $i = 1$ implies

$$U^{1*}_{G^1} = (1-\sigma)\,\phi^{1*}\phi^{2*}\left(\frac{\alpha^1 - G^{1*}}{G^{1*}}\right) - \left[\sigma + (1-\sigma)\,\phi^{1*}\right] = 0,$$

which we apply to simplify (A.4a) and (A.4b) respectively as

$$U^{2*}_{G^1}\frac{dG^{1*}}{d\alpha^2}=-\frac{dG^{1*}}{d\alpha^2}\quad\text{and}\quad U^{2*}_{G^2}\frac{dG^{2*}}{d\alpha^2}=[\sigma+(1-\sigma)\phi^{1*}]\frac{G^{1*}}{\alpha^2}-\left[\sigma+(1-\sigma)\,\phi^{2*}\right].$$

Then, adding the expressions above with that for $U^{2*}_{\alpha^2}$ in (10a) yields:

$$\frac{dU^{2*}}{d\alpha^2}=U^{2*}_{\alpha^2}+U^{2*}_{G^1}\frac{dG^{1*}}{d\alpha^2}+U^{2*}_{G^2}\frac{dG^{2*}}{d\alpha^2}=\left[\sigma+(1-\sigma)\,\phi^{1*}\right]\frac{G^{1*}}{\alpha^2}-\frac{dG^{1*}}{d\alpha^2}.$$

We now substitute G^{1*} shown in (A.1) and $dG^{1*}/d\alpha^2$ shown in (A.3) into the expression above, while using (1) that implies $\phi^{1*}=1-\sqrt{m^2/(1-\sigma)}$ in this case, to find

$$\frac{dU^{2*}}{d\alpha^2}=(1-\sigma)\left[\frac{1+m^2}{2\sqrt{m^2\,(1-\sigma)}}-1\right].\tag{A.5}$$

To see that $dU^{2*}/d\alpha^2>0$ holds for $\alpha^2\in(0,\alpha_0\,(\sigma)]$, observe that $d^2U^{2*}/(d\alpha^2)^2<0$, which implies that $dU^{2*}/d\alpha^2$ attains a minimum at $\alpha^2=\alpha_0\,(\sigma)$. But, since m^2 evaluated at $\alpha^2=\alpha_0(\sigma)$ equals $\frac{1}{4}(1-\sigma)$, we have $\lim_{\alpha^2\to\alpha_0(\sigma)}\left(dU^{2*}/d\alpha^2\right)=\frac{1}{4}\,(1+3\sigma)>0$. It follows that $dU^{2*}/d\alpha^2>0$ for all $\alpha^2\in(0,\alpha_0\,(\sigma)]$ and $\sigma\in[0,1)$.

Turning to the technology leader, we apply the same logic as above but based on (7). Specifically, using (8a) and (8b), along with $U^{1*}_{G^1}=0$, the implication of (1) that $\phi^i_{G^j}=-\phi^i\phi^j/G^i$ and our previous finding that $G^{2*}=\alpha^2$ that implies $dG^{2*}/d\alpha^2=1$, gives

$$\frac{dU^{1*}}{d\alpha^2}=U^{1*}_{\alpha^2}+U^{1*}_{G^2}\frac{dG^{2*}}{d\alpha^2}=-\left[\sigma+(1-\sigma)\,\phi^{1*}\right]\frac{G^{1*}}{\alpha^2}<0,\tag{A.6}$$

as claimed in the proposition.

Case 2, $\theta=\alpha^2$: Recalling that $G^{i*}=\widetilde{G}=\frac{1}{4}\,(1-\sigma)\left(\alpha^1+\alpha^2\right)$ for $i=1,2$ such that $\phi^{i*}=\frac{1}{2}$ for $i=1,2$ when neither country is resource constrained, the easiest way to establish this part of the proposition is to substitute these values in $U^i(G^i,G^j)$ for $i,j\in\{1,2\},\ i\neq j$ shown in (2) with $X^{i*}=\alpha^i-\widetilde{G}$; by differentiating the resulting expressions with respect to α^2, one can confirm that $dU^{1*}/d\alpha^2=\frac{1}{4}(1-\sigma)>0$ and $dU^{2*}/d\alpha^2=\frac{1}{4}(1+3\sigma)>0$.

Case 1, $\theta=\sigma$: Let us start with the technology leader. Since $\alpha^2<\alpha_0(\sigma)$ by assumption in this case, we have $G^{2*}=\alpha^2$, which implies $dG^{2*}/d\sigma=0$. Without a strategic effect for the leader, we have only with the direct effect U^{1*}_σ, which from (11) for $i=1$, simplifies as:

$$\frac{dU^{1*}}{d\sigma}=\left(\alpha^1-G^{1*}\right)(1-\phi^{1*})>0.\tag{A.7}$$

Turning to the laggard, the result that $dG^{2*}/d\sigma=0$ also implies the indirect payoff effect for the laggard through adjustments in its own arming equals zero as well. Thus, we are left to consider only the direct effect and the indirect effect that occurs through adjustments in the leader's arming choice. As shown above in our analysis of the payoff effects of changes in α^2 in case 1 by exploiting the leader's arming FOC, we have $U^{2*}_{G^1} = -1$. Thus, the total payoff effect for the laggard from an increase in σ can be written as

$$\frac{dU^{2*}}{d\sigma} = U^{2*}_{\sigma} + U^{2*}_{G^1}\frac{dG^{1*}}{d\sigma} = -\left(\alpha^1 - G^{1*}\right)\phi^{2*} - \frac{dG^{1*}}{d\sigma}.$$

To sign this expression, we use the solution for G^{1*} in (A.1), to find

$$\frac{dG^{1*}}{d\sigma} = -\frac{\alpha^2}{2\sqrt{m^2(1-\sigma)}} < 0.$$

Now observe that the solutions for G^{i*} in this case, as shown above, with (1) imply $1-\phi^{1*} = \phi^{2*} = \sqrt{m^2/(1-\sigma)}$. Combining (A.1) with the two expressions above and this result, after simplifying, yields:

$$\frac{dU^{2*}}{d\sigma} = \frac{\alpha^2}{\sqrt{m^2\,(1-\sigma)}}\left[\sqrt{m^2\,(1-\sigma)} - \frac{1}{2}\right]. \tag{A.8}$$

Since $m^2 < \frac{1}{4}(1-\sigma)$ when $\alpha^2 < \alpha_0\,(\sigma)$, the expression inside the square brackets in (A.8) is necessarily negative, implying that $dU^{2*}/d\sigma < 0$ holds in this case as needed.

Case 2, $\theta = \sigma$: The most straightforward way to study this case is to apply the assumption that $H^i = \alpha^i$ for $i = 1, 2$ with our previous finding that $G^{i*} = \widetilde{G} = \frac{1}{4}\,(1-\sigma)\left(\alpha^1 + \alpha^2\right)$ for $i = 1, 2$ to $U^i(G^i, G^2)$ shown in (2). Then, differentiating the resulting expressions with respect to σ gives $dU^{1*}/d\sigma = \frac{1}{4}[3\alpha^1 - \alpha^2] > 0$ and $dU^{2*}/d\sigma = \frac{3}{4}[\alpha^2 - \alpha_0(0)] > 0$, thereby completing the proof. ||

Proof of Proposition 3. Let us first consider the effects of increases in σ. From (12), we have $d\bar{U}^*/d\sigma = -d\bar{G}^*/d\sigma$. But, Proposition 1 establishes that $dG^{1*}/d\sigma < 0$ and $dG^{2*}/d\sigma \leq 0$ always hold (the second as a strict inequality provided the laggard diversifies its production). Thus, $d\bar{U}^*/d\sigma > 0$ always holds.

To examine the effects of improvements in technology, we breakdown the analysis into cases, 1 and 2: as before, case 1 is when the laggard specializes in appropriation and case 2 is when the laggard diversifies its production.

Case 1. Recall from the proof to Proposition 1 that the condition for agent 2 to specialize in appropriation is $m^2 \leq \frac{1}{4}(1-\sigma)$ (where $m^2 \equiv \frac{\alpha^2}{\alpha^1+\alpha^2}$) or, equivalently, $\sqrt{(1-\sigma)/4m^2} \geq 1$). Then, our previous results from the proof to Proposition 1, $dG^{2*}/d\alpha^2 = 1$ and the expression for $dG^{1*}/d\alpha^2$ shown in (A.3), imply $d\bar{G}^*/d\alpha^2 = (1+m^2)\sqrt{(1-\sigma)/4m^2} \geq 1 + m^2 > 1$. Hence, from (13), we have $d\bar{U}^*/d\alpha^2 = 1 - d\bar{G}^*/d\alpha^2 < 0$. One can also show, using (12), that $\bar{U}^* = \left(\alpha^1 + \alpha^2\right)[1 - \sqrt{(1-\sigma)\,m^2}]$, which implies $\lim_{\alpha^2 \to 0} \bar{U}^* = \alpha^1$.

Case 2. From the solution in this case where neither country is resource constrained (5), we have $\bar{G}^* = 2\widetilde{G} = \frac{1}{2}(1-\sigma)\left(\alpha^1 + \alpha^2\right)$. Thus, (12) readily implies $\bar{U}^* = \frac{1}{2}(1+\sigma)(\alpha^1+\alpha^2)$ and, therefore, $d\bar{U}^*/d\alpha^2 = \frac{1}{2}(1+\sigma) > 0$, such that $\bar{U}^*$ reaches a maximum (for $\alpha^2 \in [\alpha_0(\sigma), \alpha^1]$) at $\alpha^2 = \alpha^1$, where $\bar{U}^*|_{\alpha^2=\alpha^1} = (1+\sigma)\alpha^1$. As shown in case 1 directly above, $\lim_{\alpha^2\to 0} \bar{U}^* = \alpha^1$, a maximum value of $\bar{U}^*(\alpha^2)$ for $\alpha^2 \in [0, \alpha_0(\sigma)]$. Thus, $\bar{U}^*(\alpha^2)$ reaches a maximum for all $\alpha^2 \in (0, \alpha^1]$ at $\alpha^2 = \alpha^1$.[34] ||

A.2 Extension with Complementary Inputs and Diversified Production

Our analysis of dual-use technology transfers unveiled a noteworthy insight: technologically advanced countries might refuse to share their superior know-how to prevent laggards from using it for predatory purposes. However, the linear dependence of the countries' payoffs on butter in our baseline model implies that this refusal arises only when laggards are pure predators, because in this case they direct any improvements in their technology solely to predation. In this section, we argue that our model, though simple, captures the essence of the problem at hand and, more generally, that specialization in arming/predation is sufficient but not necessary for the validity of the insight.

To proceed, we modify the baseline model to allow for the presence of a fixed and complementary input in each country's production of butter, an input that gives rise to diminishing returns in the employment of the variable input, human capital, we had considered before. Specifically, we assume that the production function of butter in country i is given by $X^i = \left(H^i - G^i\right)^\eta$, where $\eta \in (0, 1]$ and $H^i = \alpha^i$ for $i = 1, 2$.[35] One can view η as the elasticity of butter with respect to human capital. The corresponding elasticity with respect to the complementary input (whose value is normalized to unity for simplicity and can thus be suppressed) equals $1 - \eta$. To keep the analysis simple and focused, we assume that conflict arises with certainty so that output is perfectly insecure (i.e., $\sigma = 0$). Thus, country i's payoff function can be written as: $U^i\left(G^i, G^j\right) = \phi^i \bar{X}$. Differentiation of U^i with respect to G^i gives:

$$U^i_{G^i} = \phi^i_{G^i}\left[\left(\alpha^i - G^i\right)^\eta + \left(\alpha^j - G^j\right)^\eta\right] - \phi^i\eta\left(\alpha^i - G^i\right)^{\eta-1}, \tag{A.9}$$

where $\phi^i_{G^i} = \phi^i\phi^j/G^i$ for $i, j \in \{1, 2\}$, $i \neq j$. As in the baseline model (where $\eta = 1$), the first term shows the marginal benefit of arming (MB^i_G). This term is decreasing in G^i and increasing in α^i. The second term represents the marginal cost of arming (MC^i_G) and is increasing in G^i, with $\lim_{G^i\to 0} MC^i_G = 0$, again, as in the baseline model; but, in contrast

[34] Observe further that there exists a value of α^2, $\underline{\alpha} \equiv \frac{1-\sigma}{1+\sigma}\alpha^1$ ($> \alpha_0(\sigma) = \frac{1-\sigma}{3+\sigma}\alpha^1$), such that $\bar{U}^*(\alpha^2) > \lim_{\alpha^2\to 0}\bar{U}^*$ for all $\alpha^2 \in (\underline{\alpha}, \alpha^1]$. The range of α^2 values for which this last inequality holds expands as σ rises (i.e., $d\underline{\alpha}/d\sigma < 0$).

[35] Observe that our baseline model arises as a special case of this setup when $\eta = 1$.

to that model, MC_G^i depends on α^i and negatively so provided $\eta < 1$. However, there is another important difference here. When $\eta < 1$, $\lim_{G^i \to \alpha^i} MC_G^i = \infty$, implying each country i necessarily produces both arms and butter in equilibrium.

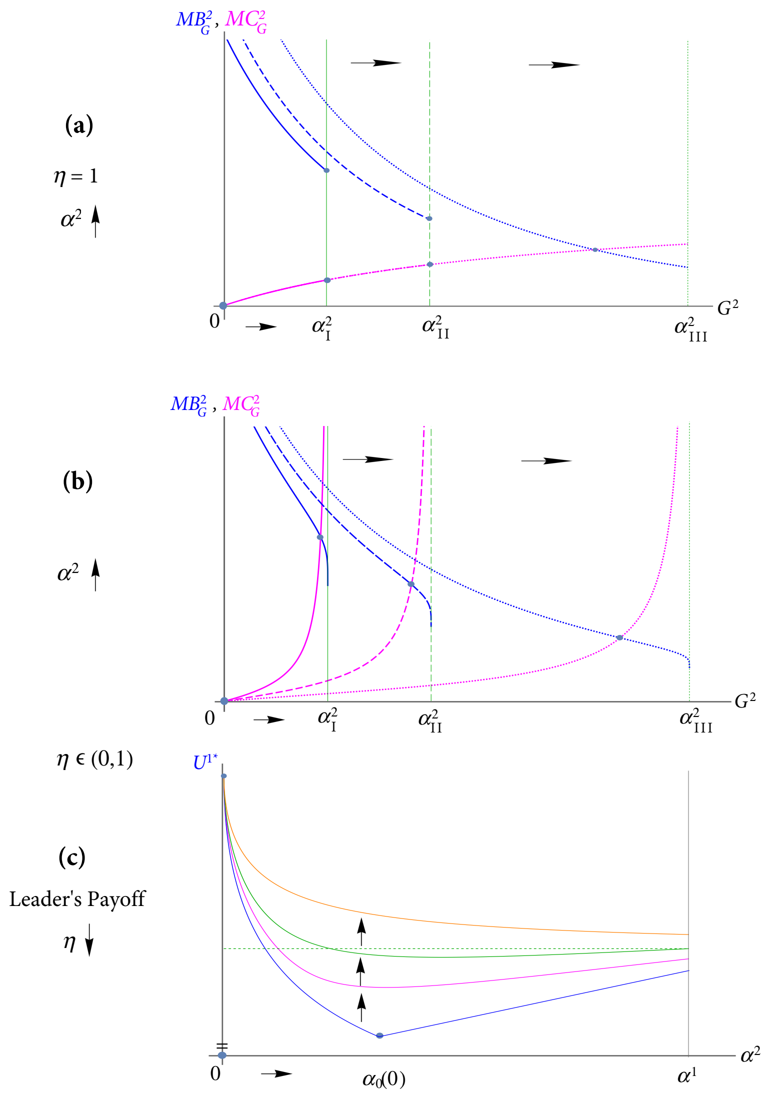

Figure A.1: Complementary Inputs and the Payoff Effects of Transfers of the Dual-Use Technology

We can visualize the above points with the help of Fig. A.1 that shows the marginal benefit and marginal cost for country 2 (the laggard). For comparison and contrast, panel (a) depicts MB_G^2 and MC_G^2 in the absence of diminishing returns (i.e., when $\eta = 1$) as functions of G^2 for several values in $\alpha^2 \in (0, \alpha^1)$ with a fixed value of G^1. As we saw earlier, when the value of α^2 is sufficiently small ($= \alpha^2_{\mathrm{I}}$ and α^2_{II} in the figure), $MB^2_G > MC^2_G$ for any feasible G^2, implying that the resource constraint on the laggard's arming choice is binding. Allowing for diminishing returns (i.e., $\eta \in (0,1)$), panel (b) illustrates the corresponding MB^2_G and MC^2_G functions for the same G^1 and the same values of α^2. Notice especially, from panel (a) that, when $\eta = 1$, MC^2_G is independent of α^2; by contrast, as shown in panel (b) when $\eta \in (0,1)$, MC^2_G rotates clockwise from the origin as α^2 rises, with MC^2_G becoming infinitely large as G^2 approaches α^2. As illustrated in panel (b), the laggard's optimal arming decision now arises at the points where $MB^2_G = MC^2_G$ even for the smaller values of α^2, thereby always ensuring the laggard's engagement in both predatory and productive activities.

One can establish that, for $\eta \in (0,1)$, this equilibrium in the arming subgame with $G^{i*} \in (0, \alpha^i)$ for $i = 1,2$ exists and is unique.[36] As before when $\eta = 1$, when $\eta \in (0,1)$ an increase in α^2 generates both a positive direct payoff effect and an adverse strategic payoff effect for each side. Furthermore, numerical analysis reveals that, when $\eta < 1$ (as was the case when $\eta = 1$), the positive payoff effect always dominates for the laggard. By contrast, the net payoff effect for the technology leader depends on the initial value of α^2.

To dig a little deeper, suppose that η is in the neighborhood of 1, so that the modified model is an approximation of the baseline model. Even though for very low values of α^2 the laggard will not specialize completely in arming and predation, its resource constraint on arming will nonetheless be very tight. As a consequence, a marginal increase in α^2 for low initial values of α^2 tends to induce the laggard to apply that increase primarily to predation. Accordingly, such improvements generate a disproportionately large strategic effect relative to the direct effect on the leader's payoff, implying that $dU^{1*}/d\alpha^2 < 0$. By contrast, when α^2 is sufficiently large to start, the resource constraint on the laggard's arming is not very tight and the direct effect of α^2 on U^{1*} prevails over the indirect effect, such that $dU^{1*}/d\alpha^2 > 0$. Panel (c) of Fig. A.1, which illustrates the dependence of U^{1*} on α^2 (and is obtained by solving the model numerically), confirms this finding for large values of η.[37] This discussion with the figure also supports the idea that our initial analysis of dual-use technology transfers remains intact and that the leader will once again find such transfers unappealing when the technological distance between countries is sufficiently large even though the laggard is not resource constrained.

However, Fig. A.1(c) also unveils another interesting (if not striking) result when the elasticity of butter production with respect to human capital η is sufficiently small. In particular, the leader's payoff U^{1*} could fall with improvements in the laggard's technology ($\alpha^2 \uparrow$) for all values of α^2 in $\left(0, \alpha^1\right)$, not just small values. The intuition here is that,

[36] Details are available in Online Appendix B.

[37] The figure suggests that, while this relationship is V-shaped in the baseline model (as noted earlier), it is U-shaped when η is strictly less than 1, but not too small.

when η is smaller to make the degree of diminishing returns in human capital stronger, the laggard tends to employ more intensively any improvement in its dual-use technology in guns production. Thus, a reduction in η tends to amplify the adverse strategic payoff effect relative to the positive direct payoff for the leader, so that $dU^{1*}/d\alpha^2 < 0$ for initially large as well as small values of α^2.[38]

In summary, complete specialization in arming is unnecessary for the validity of our finding that the leader need not grant dual-use technology transfers.[39] Perhaps more alarmingly though, in the presence of sufficiently salient complementary inputs in the production of the consumption good, the leader could find dual-use technology transfers unappealing for all possible technological distances from the laggard.

[38] See Online Appendix B for details.

[39] This finding also arises when we introduce risk aversion under the assumption that $\sigma \in (0, 1)$.

B Online Appendix: Complementary Inputs in Butter Production

In this section, we provide some technical details underlying the extension sketched out in Appendix A.2 where we considered the presence of a complementary (and fixed) input in the production of butter, that gives rise to diminishing returns in human capital the production function of butter in country i: $X^i = \left(H^i - G^i\right)^\eta$, where $\eta \in (0,1]$ and $H^i = \alpha^i$ for $i = 1,2$.[1] η represents the elasticity of butter with respect to human capital, whereas $1-\eta$ represents corresponding elasticity with respect to the complementary input whose value is normalized to unity for simplicity and can thus be suppressed. To keep the analysis simple and focused, we assume that conflict arises with certainty so that output is perfectly insecure (i.e., $\sigma = 0$) and country i's payoff function can be written as: $U^i\left(G^i, G^j\right) = \phi^i \bar{X}$. Differentiation of U^i with respect to G^i gives:

$$U^i_{G^i} = \phi^i_{G^i}\left[\left(\alpha^i - G^i\right)^\eta + \left(\alpha^j - G^j\right)^\eta\right] - \phi^i \eta \left(\alpha^i - G^i\right)^{\eta - 1}, \tag{B.1}$$

where $\phi^i_{G^i} = \phi^i\phi^j/G^i$ for $i,j \in \{1,2\}$, $i \neq j$. As argued in Appendix A.2, this condition with $\eta \in (0,1)$ implies that, in equilibrium, each country i produces both guns and butter—i.e., $U^i_{G^i} = 0$.

In what follows, we take an alternative approach to study the equilibrium in the arming subgame. This approach involves a transformation of the system of equations, $U^i_{G^i} = 0$ for $i = 1,2$ using (B.1), and turns the focus to the equilibrium values of the countries' appropriative share of contested butter and their contributive shares to the production of contested butter. As before, ϕ^i shown in (1) identifies country i's appropriative share. Country i's contributive share is given by $\psi^i \equiv X^i/\bar{X}$, where as previously defined $\bar{X} = X^1 + X^2$.

Applying this definition of ψ^i while recalling that $\phi^i_{G^i} = \phi^i\phi^j/G^i$, we can use the FOC associated country i's choice of G^i from (B.1) at an interior solution to find

$$U^i_{G^i} = 0 \implies \frac{\phi^i\phi^j}{G^i} - \frac{\eta\phi^i\psi^i}{\alpha^i - G^i} = 0, \;\; i,j \in \{1,2\}, \;\; i \neq j. \tag{B.2}$$

Now observe the following: First, the definitions of ψ^i, MB^i_G, and MC^i_G allow us to focus on the laggard's *relative* marginal benefit and its *relative* marginal cost as functions of the contributive and appropriative shares;: $MB^2_G/MB^1_G = G^1/G^2 = \phi^1/\phi^2$ and $MC^2_G/MC^1_G = \left(\phi^2/\phi^1\right)\left(\psi^1/\psi^2\right)^{(1-\eta)/\eta}$, which lead to

$$S\left(\psi^2, \phi^2, \eta\right) \equiv \frac{MB^2_G}{MB^1_G} - \frac{MC^2_G}{MC^1_G} = \frac{\phi^1}{\phi^2} - \left(\frac{\phi^2}{\phi^1}\right)\left(\frac{\psi^1}{\psi^2}\right)^{\frac{1-\eta}{\eta}} = 0 \tag{B.3}$$

[1] Our baseline model arises as a special case of this setup when $\eta = 1$.

and which, of course, holds true in equilibrium. Second, we can solve for G^i from (B.2) to obtain $G^i = \frac{\alpha^i \phi^j}{\phi^j + \eta\psi^i} < \alpha^i$ $(i, j \in \{1, 2\},\ i \neq j)$. Then, using the fact that $G^i/G^j = \phi^i/\phi^j$ with the just derived solutions for guns enables us to obtain a second relationship,

$$T\left(\psi^2, \phi^2, \alpha^2, \eta\right) \equiv \frac{\phi^1}{\phi^2} - \frac{\alpha^1 \phi^2 \left(\phi^1 + \eta\psi^2\right)}{\alpha^2 \phi^1 \left(\phi^2 + \eta\psi^1\right)} = 0, \tag{B.4}$$

which also holds true in equilibrium for $\eta \in (0, 1)$. Since $\psi^1 = 1 - \psi^2$ and $\phi^1 = 1 - \phi^2$, the system of equations in (B.3) and (B.4) defines the equilibrium values of ψ^2 and ϕ^2 implicitly as functions of countries' dual-use technologies and the elasticity of butter production with respect to human capital and helps us to characterize the equilibrium of the arming subgame, which is shown below to be unique.[2] To proceed, we study the properties of $S(\cdot) = 0$ and $T(\cdot) = 0$. Henceforth, we refer to these relationships as schedules S and T, respectively.

Starting with schedule S in (B.3) that defines ψ^2 implicitly as a function of ϕ^2, one can verify $\lim_{\phi^2 \to 0} \psi^2(\cdot)\big|_{S=0} = 0$ while $\lim_{\phi^2 \to \frac{1}{2}} \psi^2(\cdot)\big|_{S=0} = \frac{1}{2}$ for any $\eta \in (0, 1)$.[3] Furthermore, since MB_G^2/MB_G^1 is decreasing in ϕ^2 and MC_G^2/MC_G^1 is increasing in ϕ^2, $S_{\phi^2} < 0$ holds. Similarly, it is easy to confirm that MC_G^2/MC_G^1 is decreasing in ψ^2 while MB_G^2/MB_G^1 is independent of ψ^2, such that $S_{\psi^2} > 0$ holds. Bringing these two results together, we have that, for any given $\eta \in (0, 1)$, $d\psi^2/d\phi^2|_{S=0} = -S_{\phi^2}/S_{\psi^2} > 0$, which is akin to a form of complementarity. Provided $\phi^2 \in (0, \frac{1}{2})$, the range of $\psi^2(\cdot)\big|_{S=0}$ equals $(0, \frac{1}{2})$.

Next we explore how the laggard's contributive and appropriative shares compare along schedule S. Here is where the value of elasticity η comes into play. We will show that $\psi^2(\cdot)|_{S=0} \lesseqqgtr \phi^2$ as $\eta \gtreqqless \frac{1}{3}$, for any $\phi^2 \in (0, \frac{1}{2})$. Thus, in the special case of $\eta = \frac{1}{3}$, $\psi^2(\cdot)\big|_{S=0}$ is linear in ϕ^2. We will also show that $\eta > \frac{1}{3}$ (resp., $\eta < \frac{1}{3}$) implies $\psi^2(\cdot)\big|_{S=0}$ is strictly convex (resp., concave) in ϕ^2. These properties prove helpful in characterizing the leader's willingness to offer a dual-use technology transfers to the laggard.

Maintaining a focus on values of $\phi^2 \in (0, \frac{1}{2})$ (which ensures $\phi^1 > \phi^2$ and $\psi^1 > \psi^2$ along schedule S), one can easily confirm from the expression for MC_G^2/MC_G^1 $(i = 1, 2)$ that a decrease in η raises the laggard's marginal cost of arming relative to the technology leader's corresponding marginal cost:

$$\frac{\partial\left(MC_G^2/MC_G^1\right)/\partial\eta}{MC_G^2/MC_G^1} = -\frac{\ln(\psi^1/\psi^2)}{\eta^2} < 0.$$

[2] With the solutions for G^i for $i = 1, 2$ shown above, we can characterize equilibrium arming. For our purposes, however, it suffices to focus on the equilibrium shares.

[3] One can also show that $\phi^2 \to 1$ would imply $\psi^2 \to 1$ along schedule S. In fact, since the only source of asymmetry in the model is due to differences in dual-use technologies (α^1 and α^2) and these technologies do not appear in $S(\cdot) = 0$, this schedule is symmetric across countries. Here, we confine our attention to values of ϕ^2 and ψ^2 in $(0, \frac{1}{2})$ because, as we will see shortly, that is the range of equilibrium values when $\alpha^2 \in (0, \alpha^1)$.

In turn, it follows from schedule S in (B.3) that $S_\eta > 0$. Because $S_{\psi^2} > 0$ as already established, we have $d\psi^2/d\eta|_{S=0} = -S_\eta/S_{\psi^2} < 0$. In short, a reduction in the elasticity of human capital in butter production η brings about an increase in the laggard's contributive share ψ^2, for any given $\phi^2 \in (0, \frac{1}{2})$, along schedule S.

Next, define $z \equiv (\phi^1/\phi^2)^{(1-3\eta)/(1-\eta)}$ and note that, because $\phi^1/\phi^2 > 1$ for any $\phi^2 \in (0, \frac{1}{2})$, $\eta \gtreqless \frac{1}{3}$ implies $z \lesseqgtr 1$. Now observe from (B.3) that

$$S(\cdot) = 0 \implies \frac{\psi^2}{\psi^1} = \left(\frac{\phi^1}{\phi^2}\right)^{-\frac{2\eta}{1-n}} \implies \frac{\psi^2/\phi^2}{\psi^1/\phi^1} = z.$$

Using the fact that $\psi^1 = 1 - \psi^2$ allows us to transform the last equality shown above as $1 - \psi^2/\phi^2 = (1-z)/\left(1 + z\phi^2/\phi^1\right)$. Hence, $\eta \gtreqless \frac{1}{3}$ implies $\phi^2 \gtreqless \psi^2|_{S=0}$. In addition, we can again use the fact that $\psi^1 = 1 - \psi^2$ with the second equality above to find an explicit solution for $\psi^2|_{S=0}$: $\psi^2|_{S=0} = [1 + (\phi^1/\phi^2)^{\frac{2\eta}{1-\eta}}]^{-1}$. Keeping in mind that $\phi^1 = 1 - \phi^2$, we differentiate $\psi^2|_{S=0}$ twice with respect to ϕ^2 to arrive at

$$\text{sign}\left\{\left.\frac{d^2\psi^2}{(d\phi^2)^2}\right|_{S=0}\right\} = \text{sign}\left\{\phi^2 - \psi^2 + \frac{3}{1-\eta}\left(\eta - \tfrac{1}{3}\right)\overbrace{\left(\tfrac{1}{2} - \psi^2\right)}^{(+)}\right\}.$$

With our focus on values of $\psi^2 \in (0, \frac{1}{2})$, an application of the finding that $\phi^2 \gtreqless \psi^2|_{S=0}$ as $\eta \gtreqless \frac{1}{3}$ to the RHS of the above expression allows us to infer that $\eta \gtreqless \frac{1}{3}$ implies $d^2\psi^2/(d\phi^2)^2|_{S=0} \gtreqless 0$, as claimed above.[4] The important insight here is that the elasticity of butter with respect to human capital η shapes the equilibrium relationship between the contributive and appropriative shares governed by schedule S.

For clarity, we illustrate the functions $\psi^2\left(\phi^2, \eta\right)|_{S=0}$ associated with schedule S in panel (a) of Fig. B.1 for three values of η: $\eta = \frac{1}{3}$, $\eta' > \frac{1}{3}$, and $\eta'' < \frac{1}{3}$. This panel also illustrates the following noteworthy features of schedule S:

(a) $\lim_{\phi^2 \to 0}\left(\psi^2(\cdot)\big|_{S=0}\right)/\phi^2 = 0$ when $\eta > \frac{1}{3}$.

(b) $\lim_{\phi^2 \to 0}\left(\psi^2(\cdot)\big|_{S=0}\right)/\phi^2 = \infty$ when $\eta < \frac{1}{3}$.

(c) $\lim_{\phi^2 \to 0}\left(\psi^2(\cdot)\big|_{S=0}\right)/\phi^2 = 1$ when $\eta = \frac{1}{3}$.

Once again, these features have useful implications for the payoff effects of the laggard's dual-use technology. However, before getting to those implications, we need to characterize the properties of schedule T.

Schedule T shown in (B.4) implicitly defines the second relationship between ψ^2 and ϕ^2

[4] Inspection of the above equation also reveals that $\lim_{\phi^2 \to 0}(d^2\psi^2/(d\phi^2)^2|_{S=0}) = 0$, which signals the presence of an inflection point.

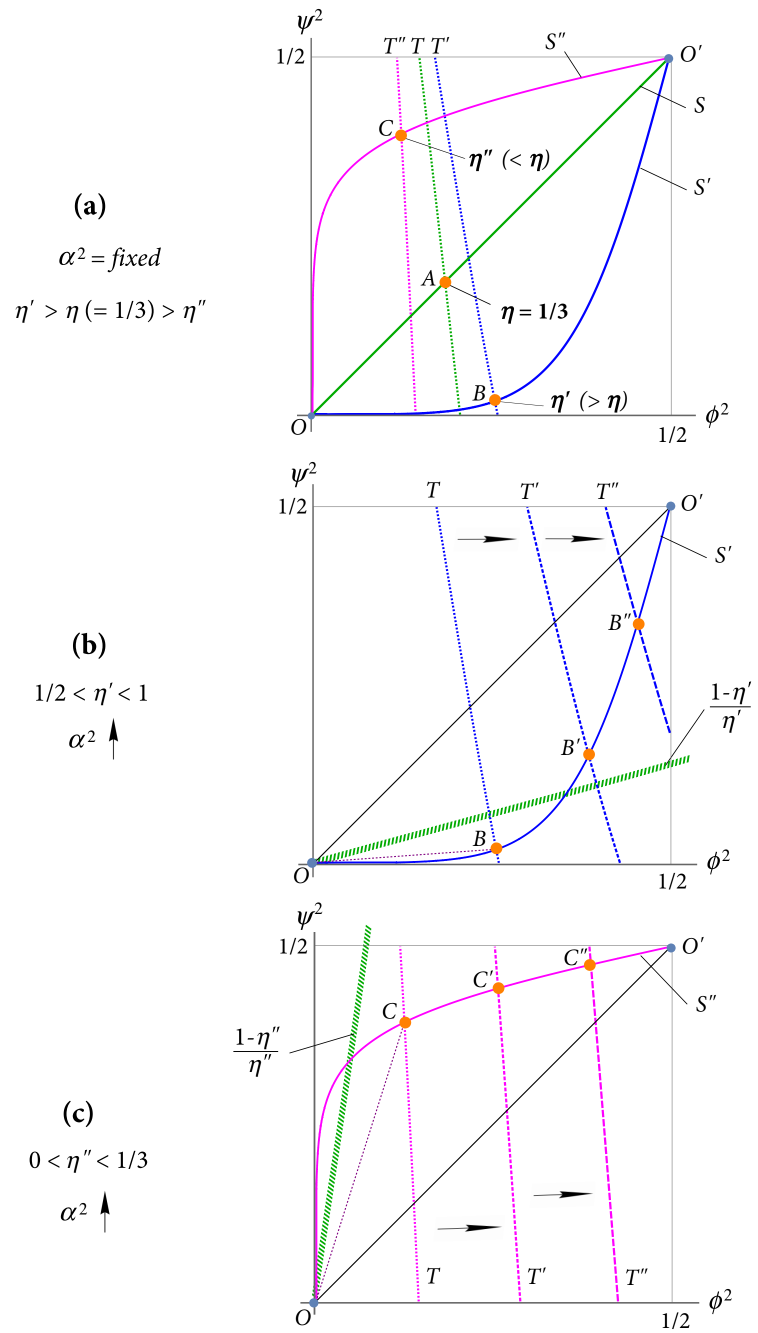

Figure B.1: The Effects of Changes in Dual-Use Technology and the Elasticity of Human Capital in Butter Production on Equilibrium Shares.

that also arises in equilibrium. Partial differentiation of $T(\cdot)$ gives

$$\begin{aligned}
T_{\phi^2} &= -\left(\phi^2\right)^{-2}\left(1+\phi^1\frac{\eta\psi^1}{\phi^2+\eta\psi^1}+\phi^2\frac{\eta\psi^2}{\phi^1+\eta\psi^2}\right)<0 \\
T_{\psi^2} &= -\eta\left(\phi^1/\phi^2\right)\left(\frac{1}{\phi^2+\eta\psi^1}+\frac{1}{\phi^1+\eta\psi^2}\right)<0 \\
T_{\eta} &= \left(\phi^1/\phi^2\right)\left[\frac{\phi^1\psi^1-\phi^2\psi^2}{\left(\phi^2+\eta\psi^1\right)\left(\phi^1+\eta\psi^2\right)}\right]\gtreqless 0 \ \text{ as } \ \phi^1\psi^1\gtreqless\phi^2\psi^2 \\
T_{\alpha^2} &= \frac{\phi^1/\phi^2}{\alpha^2}>0.
\end{aligned}$$

From the above, one can see that $d\psi^2/d\phi^2|_{T=0} = -T_{\phi^2}/T_{\psi^2} < 0$; therefore, schedule T is downward sloping as shown in the panels of Fig. B.1. In view of the symmetric structure of schedule T, it should be clear that $\psi^2 = \phi^2 = \frac{1}{2}$ is a point on the schedule when $\alpha^2 = \alpha^1$. Given that $T_{\alpha^2} > 0$ and our focus on $\alpha^2 \in (0, \alpha^1)$, it should also be clear that schedule T cuts the upper horizontal axis (i.e., where $\psi^2 = \frac{1}{2}$) at some point $\phi^2 < \frac{1}{2}$.[5]

These properties of schedule T together with the fact that schedule S is upward sloping imply that, for any given $\alpha^2 \in (0, \alpha^1)$, these schedules will cross each other at a unique point, the equilibrium shares $\left(\phi^{2*}, \psi^{2*}\right) < \left(\frac{1}{2}, \frac{1}{2}\right)$. Since $\phi^{1*}\psi^{1*} > \phi^{2*}\psi^{2*}$ at this equilibrium, we will have $T_\eta > 0$; therefore, reductions in η shift schedule T leftward. Panel (a) in Fig. B.1 illustrates the equilibria that are associated with alternative values of η.

Let us now study the effects of improvements in the laggard's technology ($\alpha^2 \uparrow$) perhaps due to a technology transfer. Observe that, while schedule S is independent of α^2, $T_{\alpha^2} > 0$. Since an increase in α^2 effectively reduces the laggard's relative marginal cost of producing guns, an improvement in the laggard's technology implies a larger value of ϕ^2 for each value of ψ^2 along that curve. This effect is illustrated in panels (b) and (c) of Fig. B.1. In panel (b) assuming $\eta > \frac{1}{3}$, the associated equilibria are depicted by points B, B' and B''; and in panel (c) where $\eta < \frac{1}{3}$, the associated equilibria are depicted by points C, C' and C''. Importantly, in both cases, these productivity improvements induce the laggard to increase both its equilibrium appropriative (ϕ^{2*}) and its contributive (ψ^{2*}) shares. However, there is an important difference. When $\eta > \frac{1}{3}$ (panel (b)), the laggard's contributive share rises relative to its appropriative share (i.e., $\psi^{2*}/\phi^{2*} \uparrow$) due to the strict convexity of $\psi^2\big|_{S=0}$ in ϕ^2 (i.e., schedule S) discussed earlier. In contrast, when $\eta < \frac{1}{3}$ (panel (c)), the ratio ψ^{2*}/ϕ^{2*} falls due to the strict concavity of schedule S. These findings play key roles in the welfare analysis below.

As in the baseline model where $\eta = 1$, an improvement in the laggard's technology ($\alpha^2 \uparrow$) generates a positive direct payoff effect and an adverse strategic payoff effect for each

[5] On a more technical note, observe that the partial derivatives of $T(\cdot)$ shown above make economic sense only for $\phi^2 \in (\underline{\phi}^2, \bar{\phi}^2)$, where $\underline{\phi}^2 = \phi^2(1)|_{T=0} < \bar{\phi}^2 = \phi^2(0)|_{T=0}$ along schedule T.

side. Focusing on the leader, differentiation of its payoff with respect to α^2, while using the laggard's FOC for arming, delivers

$$\frac{dU^{1*}/d\alpha^2}{U^{1*}} = \frac{1}{G^{2*}}\left[\phi^{1*} - \frac{dG^{2*}}{d\alpha^2}\right]. \tag{B.5}$$

The first term inside the brackets is associated with the direct effect and the second term with the indirect effect noted above. It is a straightforward to show that

$$\frac{dG^{2*}}{d\alpha^2} = \frac{\phi^{1*}\left(1-\eta+\eta\psi^{2*}\right)}{(1-\eta)\,\phi^{1*}+2\eta\psi^{2*}} > 0, \tag{B.6}$$

thereby confirming the point that the strategic effect of increasing α^2 on U^{1*} is negative. The key question here is how these conflicting payoff effects compare to each other. Substituting (B.6) into (B.5) and simplifying the resulting expression allows us to recalculate the net effect as follows:

$$\begin{aligned}\frac{dU^{1*}/d\alpha^2}{U^{1*}} &= \frac{\phi^{1*}}{G^{2*}}\left[1-\frac{1-\eta+\eta\psi^{2*}}{(1-\eta)\,\phi^{1*}+2\eta\psi^{2*}}\right]\\ &= \frac{\eta\phi^{1*}\phi^{2*}}{G^{2*}\left[(1-\eta)\,\phi^{1*}+2\eta\psi^{2*}\right]}\left[\frac{\psi^{2*}}{\phi^{2*}}-\frac{1-\eta}{\eta}\right].\end{aligned} \tag{B.7}$$

Clearly, the sign of the net effect of α^2 on the leader's payoff depends on how the ratio of its contributive share over its appropriative share (i.e., ψ^{2*}/ϕ^{2*}) compares with the ratio of elasticities in butter associated with the complementary input and human capital (i.e., $(1-\eta)/\eta$). Ceteris paribus, the more extensive is the laggard's use of the technology and its resources in the production of butter as compared with the production of guns, the more likely it is that the leader will find a technology transfer appealing. This is so because increases in ψ^{2*}/ϕ^{2*} tend to reduce the intensity of the adverse strategic effect of arming. But, there is another side to this. The lower is the value of η, the stronger is the laggard's arming response to increases in α^2.

To dig deeper, suppose $\eta = \frac{1}{3}$ (so that $\frac{1-\eta}{\eta} = 2$ in (B.7)) and recall from our analysis of schedule S that $\psi^{2*} = \phi^{2*}$ in this case. Since $dU^{1*}/d\alpha^2 < 0$ for all $\alpha^2 \in (0, \alpha^1)$, the technology leader now finds dual-use technology transfers unappealing. Note that this stands in sharp contrast to the related result in the baseline model.

Next, fix η at some level in $[\frac{1}{2}, 1)$, so that $\frac{1-\eta}{\eta} \in (0, 1]$, as indicated by the slope of the green dashed-line ray from the origin in panel (b) of Fig. B.1. Now let α^2 rise gradually from very low levels all the way to α^1, so that the equilibrium moves from point O, to points B, B', B'' and eventually to point O' on schedule S. At low levels of α^2 the sign of $dU^{1*}/d\alpha^2$ is negative. However, when α^2 becomes sufficiently large, $dU^{1*}/d\alpha^2$ becomes positive. This suggests that U^{1*} is U-shaped in α^2 when $\eta \in [\frac{1}{2}, 1)$. Interestingly, if we considered values of $\eta \in (\frac{1}{3}, \frac{1}{2}]$, so that $\frac{1-\eta}{\eta} \in (1, 2]$, the slope of the green ray would exceed 1, and U^{1*} would unambiguously decrease with increases in α^2 throughout its domain.

Turning to $\eta \in (0, \frac{1}{3})$, which implies $\psi^2\left(\phi^2, \eta\right)\big|_{S=0}$ is strictly concave in ϕ^2 as shown in panel (c) of Fig. B.1, successive increases in α^2 now shift the equilibrium from point O to points C, C', C'' and eventually to point O' on schedule S. In this case, at very low levels of α^2, the ratio ψ^{2*}/ϕ^{2*} starts at high values ($> \frac{1-\eta}{\eta}$), crosses $\frac{1-\eta}{\eta}$, and eventually falls to 1. Thus, U^{1*} falls for most values of α^2, as illustrated in panel (c) of Fig. A.1 of Appendix A.4 of the paper. It is conceivable that U^{1*} rises with increases in α^2 at sufficiently low levels of α^2. In this case (not shown in Fig. A.1c)), U^{1*} would attain a maximum. However, numerical analysis of the model reveals that this possibility arises only when η is extremely small.