TECHNOLOGICAL PROGRESS AND RENT SEEKING *

Vincent Glode Guillermo Ordoñez

University of Pennsylvania

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Abstract

We model firms' allocation of resources across surplus-creating (i.e., productive) and surplus-appropriating (i.e., rent-seeking) activities. Our model predicts that industry-wide technological advancements, such as recent progress in data collection and processing, generically induce a disproportionate and socially inefficient reallocation of resources towards surplus-appropriating activities. As technology improves, firms rely more on appropriation to obtain their profits, endogenously reducing the impact of technological progress on economic progress and inflating the price of the resources used for both types of activities. We apply our theoretical insights to shed light on the rise of high-frequency trading.

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The last few decades have featured exceptional technological progress, as evidenced for example by striking increases in computer processing power (see, e.g., Roser and Ritchie 2013), data availability (see, e.g., Durant 2020), and patented innovation (see, e.g., Kelly et al. 2021). Standard economic theories have highlighted the importance of technological progress that boosts firms' productivity in generating long-term economic growth. Yet, in light of the observed technological progress, global economic growth has surprisingly slowed down in recent decades.[1] Some have attributed this phenomenon, sometimes referred to as the "productivity paradox" or the "Solow paradox", to productivity mismeasurements, to lags in technology adoption, or even to information technologies and social media distracting workers (see, e.g., Brynjolfsson, Benzell, and Rock 2020).

Omitted from the discussion, however, is the impact of technological progress on rent-seeking behaviors in the economy. A large variety of prevalent economic activities can fit into a broad definition of "rent seeking", including imitating competing firms' innovations, suing wealthy defendants, lobbying or bribing government officials, taking advantage of financial counterparties' liquidity needs, and increasing the markups charged to unsophisticated customers. While all these activities might, at first, appear to be disparate in light of their different institutional settings, they all share the same objective of appropriating others' wealth without creating much benefit for society as a whole. Transferring wealth or economic surplus across agents is not by itself socially costly, but as pointed out by Tullock (1967, 1980), investing scarce resources in activities aimed at influencing these transfers is "a negative-sum game" when these resources could have been invested in more socially productive activities. Given the wide array of activities that fit this description, we study how rent-seeking opportunities influence the relationship between technological progress and economic output through a stylized, yet flexible model that captures the surplus-appropriation objective common to all of these activities.

Specifically, we model firms' privately optimal allocation of resources between surplus-creating (i.e., productive) and surplus-appropriating (i.e., rent-seeking) activities. Our model's central prediction is that firms respond to industry-wide technological progress by disproportionately reallocating resources towards surplus-appropriating activities, thereby mitigating the positive impact of technological progress on economic output that has been the focus of the literature so far. While this prediction might appear trivial for

[1] See global economic growth statistics compiled by the World Bank at: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG.

innovations that mainly facilitate surplus appropriation, it holds in our environment even for innovations resulting in productivity gains that are far larger for surplus-creating activities than for surplus-appropriating activities. In fact, as long as a technological innovation ameliorates *to some extent* firms' ability to appropriate their rivals' surplus, firms respond to it by shifting a larger share of their resources towards surplus appropriation.

This stark prediction originates from two insights related to how technological progress affects firms' profits. First, industry-wide improvements in technologies used to appropriate other firms' surplus amplify the payoff of investing in surplus-appropriating activities and reduce the payoff of investing in surplus-creating activities, since rivals are more successful in their surplus-appropriating efforts. Second, and more surprisingly, industry-wide improvements in technologies used to create surplus amplify the payoffs of both activities in lockstep, since efforts to appropriate other firms' surplus become more profitable when these other firms have more surplus to appropriate. Altogether, these insights imply that industry-wide technological innovations that improve firms' abilities to create as well as to appropriate economic surplus, albeit to possibly different extents, disproportionately incentivize firms to appropriate their rivals' surplus instead of creating additional surplus. As technology keeps improving, the economy gradually moves from a *productive* economy to a *rent-seeking* economy, thereby weakening the link between technological progress and economic progress.

The disproportionate allocation of resources to non-productive activities may also raise the price of resources above what it would be in a benchmark economy without rent seeking. Thus, the negative pressure of technological advancements on the economy does not only manifest itself in a higher share of the economy's resources being inefficiently allocated to surplus-appropriating activities, but also in a higher price paid for the resources needed to perform these activities, which often happen to be the same kind of resources that are used to create social surplus (e.g., human capital).

We first illustrate these general economic insights using a transparent, yet flexible model. We then identify the properties that are required to deliver those same predictions in a more general environment. Finally, we apply our insights to the financial sector, which has been argued to combine surplus creating and appropriating activities (see, e.g., Hirshleifer 1971, Baumol 1990, Murphy, Shleifer, and Vishny 1991, French 2008, Greenwood and Scharfstein 2013, Zingales 2015). Specifically, we extend our baseline model to accommodate a high-frequency trading context, which features trading firms that allocate resources between market-making and predatory-trading activities. Applying our conceptual insights to high-frequency trading is motivated by the many experts who have argued that the sector exhibits socially excessive investments (see, e.g., Schwartz and Wu 2013, Biais, Foucault, and Moinas 2015, Budish, Cramton, and Shim 2015, Pagnotta and Philippon 2018) and that its rising economic importance has mostly been driven by recent developments in processing, communication, and information technologies (see, e.g., Goldstein, Kumar, and Graves 2014, Lewis 2014, MacKenzie 2021). This application highlights how many characteristics of the financial sector, such as financial intermediaries' market power, their ability to match clients' trades internally, and their price impact in interdealer markets, among others, contribute to our paper's main prediction that industry-wide technological progress generically leads to resources being disproportionately allocated towards surplus-appropriating activities, such as electronic front-running.

Literature review. Our paper contributes to the large literature connecting technological progress and economic growth. In the celebrated model of Solow (1957), long-term economic growth is driven along the balance-growth path by the growth rate of productivity, which is purely determined by technological improvements.[2] Our work incorporates firms' choice to allocate resources to rent-seeking activities and shows that the sensitivity of economic growth to technological progress weakens over time due to the endogenously increasing prevalence of those activities. In this sense, rent seeking should be added to the forces commonly identified in the literature (see, e.g., Barro 1999) as being part of the Solow residual, such as spillovers, increasing returns, taxes, and various types of factor inputs. Further, we should expect this "rent-seeking residual" to increase with technological progress and to become more significant over time.

The seminal paper by Murphy, Shleifer, and Vishny (1991) studies workers' occupational choice between productive and rent-seeking sectors, and emphasizes how this choice depends on the returns to ability and to scale in the two occupations. When the returns from rent seeking increase in the intensity of rent-seeking efforts, multiple equilibria might exist and workers' occupational choices may lead to lower growth, a channel that is further highlighted in Murphy, Shleifer, and Vishny (1993). While these papers already make the case that rent seeking slows down economic progress through workers' occupational choices, we study firms' decision to allocate resources at an intensive margin, not present in models of occupational

[2] In contrast to Solow (1957), Crouzet et al. (2022) show that the transmission of ideas (i.e., the degree of non-rivalry) non-monotonically affects firms' incentives to innovate and compete, which determine long-run economic growth.

choices: all agents in our model (i.e., firms) can simultaneously create surplus and appropriate others' surplus. Hence, we are able to apply our insights to several decisions besides choosing one's own occupation. Moreover, unlike in those papers, our analysis investigates the impact of concurrent productivity improvements in *both* types of activities: surplus creation and appropriation. These differences make our setting particularly amenable to being applied to broad sectors and to general-purpose innovations.

Another related literature studies the optimal taxation of income generated by economic activities that introduce negative externalities, like rent seeking in our model. Lockwood, Nathanson, and Weyl (2017) measure the negative externalities of several sectors, and conclude that rent-seeking behaviors are particularly prominent in the financial and legal sectors. Their evidence is cited by Rothschild and Scheuer (2016) to justify adjusting taxation schemes to account for rent-seeking externalities and thereby reduce the inefficient allocation of talent (see also Scheuer and Slemrod 2021, for a discussion specifically focused on the role played by a wealth tax). In an environment with heterogenous beliefs, Dávila (2023) studies the optimal taxation of transactions that may or may not improve the efficient allocation of financial assets. Our analysis highlights that technological progress amplifies the prevalence of rent seeking in the economy, thereby emphasizing the increasing importance of designing policies that curb the inefficient allocation of talent and other scarce resources towards surplus-appropriating activities.

By applying our general insights in a high-frequency trading context, we contribute to a better understanding of the financial sector's resource allocation and its social efficiency, as urged in Zingales' (2015) Presidential Address to the American Finance Association. Philippon (2010), Glode, Green, and Lowery (2012), Fishman and Parker (2015), Glode and Lowery (2016), Farboodi et al. (2019), Biais and Landier (2020), and Berk and van Binsbergen (2022) all study models in which resources are invested in financial activities that do not benefit society. Closer to our application, Biais, Foucault, and Moinas (2015), Budish, Cramton, and Shim (2015), Foucault, Kozhan, and Tham (2017), Menkveld and Zoican (2017), and Pagnotta and Philippon (2018) highlight traders' various incentives to make speed-enhancing investments that promote surplus appropriation. We contribute to this literature by showing how the scale and compensation associated with various trading activities respond, in equilibrium, to waves of technological innovation.

Our analysis of the equilibrium price of resources also relates our paper to the literature on the compensation of superstars and other scarce resources, which identifies conditions under which the prices of production factors may appear to be excessive (see, e.g., Rosen 1981). Our insights can be used to understand why Greenwood and Scharfstein (2013) observe positive trends in the relative economic importance of the financial sector, including activities that match our description of surplus appropriation, while Philippon and Reshef (2012) and Célérier and Vallée (2019) observe large increases in the prices paid for an essential resource in this sector: skilled workers.

Finally, our paper relates to the burgeoning literature studying the economic impacts of recent technological improvements in the collection, the processing, and the management of big data. Farboodi and Veldkamp (2020) highlight how improvements in information technology induce traders to focus on acquiring information about others' trades rather than about assets' fundamental values. Farboodi and Veldkamp (2022) emphasize the complementarity between data accumulation and firm size. Gaballo and Ordoñez (2022) point toward the trade-off between the benefits of information for production and the costs for risk sharing, and its effect on the generation of safe assets. Although our paper differs by linking technology and economic progress through the allocation of resources towards surplus appropriation, it shares with this literature the call for a better understanding of the nuanced impacts of new information technologies.

1 Baseline Model

Suppose a firm $i \in I$ has a positive supply of resources denoted b_i. The firm can choose to allocate a quantity $s_i \geq 0$ of resources to *create* (social) surplus using a production function $\pi_i(s_i)$, and a quantity $x_i \geq 0$ of resources to *appropriate* a fraction $\alpha_i(x_i) \in [0,1]$ of a rival firm's surplus, such that $s_i + x_i \leq b_i$. To fix ideas, it might help to think of these resources as labor, and each firm chooses how to allocate its workforce between two different activities. For simplicity, assume for now that firm i has a single rival $j \neq i$ in the industry from which it can appropriate surplus, and vice-versa. Firm i's payoff is then given by:

$$\Omega(x_i, s_i, x_j, s_j) \equiv \pi_i(s_i) \cdot [1 - \alpha_j(x_j)] + \pi_j(s_j) \cdot \alpha_i(x_i). \tag{1}$$

By having $\alpha_i(x_i)$ multiplying $\pi_j(s_j)$ and vice-versa, the assumed payoff function aims to cleanly capture the simple, yet general idea that efforts to appropriate others' surplus are more profitable when others have more surplus to appropriate.[3] In our model, the term $\pi_j(s_j) \cdot \alpha_i(x_i)$ represents a transfer from firm j to firm i, which per se does not reduce the overall surplus in the economy. As Tullock (1967, 1980) discusses in the context of activities such as theft, however, appropriation ends up reducing the total social surplus in our environment because a quantity $x_i > 0$ of firm i's resources could have been allocated to creating more surplus instead.[4]

We keep our baseline setting as streamlined and flexible as possible with the objective of capturing intuitively how technological improvements in surplus creation and appropriation differentially affect the allocation of resources. We generalize this simple setting in subsection 2.5 to highlight the general conditions under which our main predictions hold, as well as identify their limitations. We also provide micro-foundations for payoff function (1) in the context of high-frequency trading in Section 3. This application also shows how our results survive various context-relevant modifications to our baseline environment. For instance, we extend the analysis to allow each firm's resources x_i to also help protect its surplus from appropriation efforts by $(N-1)$ rival firms. For now, the only restrictions we impose on payoff function (1) are that, for all $i \in I$, $\pi_i(\cdot)$ and $\alpha_i(\cdot)$ are increasing, concave functions and $\alpha_i(\cdot) \in [0,1]$.

Given payoff function (1), firm i allocates its resources to satisfy the first-order condition:

$$\pi_i'(s_i) \cdot [1 - \alpha_j(x_j)] = \pi_j(s_j) \cdot \alpha_i'(x_i),$$

with $s_i + x_i = b_i$.

Firm-specific technological progress. In order to model technological progress, we assume for now that each firm's surplus-creation function $\pi_i(\cdot)$ and surplus-appropriation function $\alpha_i(\cdot)$ can be decomposed into an exogenous firm-specific technology parameter and a concave function of the resources the firm invests in that specific activity. That is, we let $\pi_i(s_i) \equiv \phi_{y,i} \cdot y(s_i)$ and $\alpha(x_i) \equiv \phi_{a,i} \cdot a(x_i)$. This parameterization implies that increases in productivity come from technological changes improving *total factor productivity*

[3]This focus on surplus appropriation contrasts our environment from Hirshleifer's (1995), where rent-seeking efforts are modeled as resource-appropriation attempts. Skaperdas (1992) also studies the equilibrium properties of various functional forms for the rent-seeking output, but does not consider technological progress and its economic implications, which are the focus here.

[4]A firm may also inefficiently allocate resources to protect its surplus from rival firms' appropriation efforts, a possibility we later capture by allowing a more general function $\alpha(x_i, x_j)$. It is also possible that appropriation efforts induce deadweight losses (i.e., $\pi_j(s_j) \cdot \alpha_i(x_i)$ is not a clean transfer from firm j to firm i), but this extension would strengthen the notion that allocating resources to surplus appropriation is socially inefficient.

The firm's first-order condition then becomes:

$$\phi_{y,i} \cdot y'(s_i) \cdot [1 - \phi_{a,j} \cdot a(x_j)] = \phi_{y,j} \cdot y(s_j) \cdot \phi_{a,i} \cdot a'(x_i).$$

with $s_i + x_i = b_i$. Fixing j's actions, this first-order condition characterizes firm i's best response, and generates intuitive implications. When firm i becomes individually more productive in creating surplus (i.e., when $\phi_{y,i}$ increases), the firm finds it optimal to allocate more resources towards surplus-creating activities. When instead firm i becomes individually more productive in appropriating surplus from the other firm (i.e., when $\phi_{a,i}$ increases), the firm finds it optimal to allocate more resources towards surplus-appropriating activities. Together, we get the natural implication that each firm responds to a firm-specific technological advancement by tilting its allocation of resources towards the activities whose productivity benefits most from the advancement. This reallocation is firm i's best response to *firm-specific* improvements in technology. In the next section, we analyze firms' best responses to *industry-wide* improvements in technology, and characterize the unique symmetric equilibrium, in which both firms create and appropriate surplus.

2 Industry-Wide Technological Progress

We now investigate how firms' resource allocations change with technological advancements impacting all firms within an industry (e.g., increased availability of data, more powerful computers, improved communication and transportation capabilities). To keep our analysis of industry-wide technological progress tractable, we impose symmetry such that $\phi_{a,i} = \phi_{a,j} \equiv \phi_a$ and $\phi_{y,i} = \phi_{y,j} \equiv \phi_y$. We also assume that these technology parameters are exogenous to firms' actions.[5] In such parametrization, firm i's first-order condition becomes:

$$y'(s_i) \cdot [1 - \phi_a \cdot a(x_j)] = y(s_j) \cdot \phi_a \cdot a'(x_i), \tag{2}$$

with $s_i + x_i = b_i$. Firm i's best response to industry-wide technological progress reveals two insights about firms' optimal allocation of resources. On the one hand, the industry-wide productivity of surplus-appropriating activities, ϕ_a, affects firm decisions in unsurprising ways. Ceteris paribus, a higher ϕ_a implies

[5] Note that the function $y(s_i)$ can in principle also incorporate how firm i's resources create surplus by generating firm-specific technological innovations.

that firm i will be more successful in its attempts to appropriate the surplus that firm j creates and firm j will be more successful in its attempts to appropriate the surplus that firm i creates. Thus, the right-hand side of (2) is higher while the left-hand side is lower. As a result, fewer resources get allocated to surplus creation, s_i, and more resources get allocated to surplus appropriation, x_i, in response to an industry-wide improvement in the productivity of firms' surplus-appropriating activities, ϕ_a.

On the other hand, the industry-wide productivity of surplus-creating activities, ϕ_y, disappears from the first-order condition and therefore does not impact the optimal allocation of resources. The intuition behind this more surprising insight is that the associated technological progress boosts a firm's rewards to surplus creation in the same proportion it boosts the rewards from appropriating its rival's now-larger surplus. Indeed, improvements in surplus-creating technologies do not solely make surplus-creating efforts more beneficial for a firm, they also imply that its rival is more productive in creating the surplus that is available for appropriation.

2.1 Allocation of resources in equilibrium

The previous analysis of a firm's best response to technological progress highlighted a surprising asymmetry in how a firm responds to advancements associated with surplus creation versus surplus appropriation. We now explore how firms' best responses evolve into an equilibrium.

Since firm i is expected to reallocate resources towards surplus appropriation in response to technological progress that boosts ϕ_a, the marginal benefit firm j accrues from creating more surplus might decrease even if ϕ_y increases. Moreover, the impact of technological progress on the marginal benefit of appropriating firm i's surplus combines a decrease in resources invested in surplus creation by firm i with a higher productivity per unit invested. To understand how all these effects combine in equilibrium, we now characterize the equilibrium allocations for a pair of symmetrically-impacted and behaving firms. Dispensing with the sub-indices i and j, recognizing that optimally $s+x=b$, and denoting equilibrium allocations with an asterisk, the first-order condition from equation (2) can now be written as:

$$y'(b-x^*)\cdot[1-\phi_a\cdot a(x^*)]-y(b-x^*)\cdot\phi_a\cdot a'(x^*)=0. \tag{3}$$

If we differentiate the left-hand side of (3) with respect to x^*, we get:

$$-y''(b-x^*)\cdot[1-\phi_a\cdot a(x^*)]-y(b-x^*)\cdot\phi_a\cdot a''(x^*),$$

which is strictly positive whenever either $a(\cdot)$ is strictly concave or $y(\cdot)$ is strictly concave and $\alpha(x^*) = \phi_a \cdot a(x^*)$ remains a fraction smaller than 1. Thus, under fairly standard assumptions, the first-order condition in (3) can only be satisfied with one level of x^* and, as a result, there exists only one symmetric equilibrium.

Analogous to the insights obtained when analyzing firm i's best response, any change in the productivity of surplus creation ϕ_y that is not associated with a change in ϕ_a would have no impact on the equilibrium allocation of resources in the economy. The equilibrium allocation of resources between surplus-creating and surplus-appropriating activities only depends on the absolute productivity of the latter (i.e., ϕ_a), regardless of the level of the former (i.e., ϕ_y). By applying the implicit function theorem to the first-order condition (3), we can observe how the equilibrium resource allocation in surplus appropriation, x^*, responds to marginal changes in ϕ_a:

$$\frac{\partial x^*}{\partial \phi_a} = -\frac{y'(b-x^*)\cdot a(x^*)+y(b-x^*)\cdot a'(x^*)}{y''(b-x^*)\cdot[1-\phi_a\cdot a(x^*)]+y(b-x^*)\cdot\phi_a\cdot a''(x^*)}. \tag{4}$$

This expression is strictly positive whenever either $a(\cdot)$ is strictly concave or $y(\cdot)$ is strictly concave and $\alpha(x^*)$ remains a fraction smaller than 1. Thus, under the same fairly standard assumptions as above, technological progress is expected to lead to more resources being allocated to surplus appropriation. Yet, as we show below, while improvements in ϕ_a reduce firms' allocations of resources to surplus creation, the social surplus firms create may still increase with technological progress as long as those fewer resources are relatively more productive given the increase in ϕ_y.

The central prediction of the paper can thus be summarized as follows: while technological advancements that increase the productivity of surplus-creating activities at an industry level do not lead to a reallocation of resources towards surplus creation, technological advancements that increase the productivity of surplus-appropriating activities at an industry level do lead to a reallocation of resources towards surplus appropriation. That is, technological progress has an asymmetric effect on firms' optimal resource allocation. Industry-wide technological progress, which generically boosts the productivity of both types of activities albeit to different extents, therefore causes a disproportionate shift of resources towards surplus appropriation in equilibrium.

These results call into question the effectiveness of policies aimed at boosting the productivity of surplus-creating activities without also addressing the induced inefficient reallocation of resources towards surplus-appropriating activities. Intuitively, any intervention that expands the surplus firms create also boosts their rivals' incentives to invest in appropriating this now-larger surplus. Instead, policymakers should focus on reducing the productivity and profitability of surplus appropriation (e.g., by taxing more the returns to appropriation activities, penalizing their operation, or improving property rights).

2.2 Price of resources

We now consider what happens when firms have to compete for the resources they plan to allocate to the different activities. Instead of being endowed with a symmetric budget of resources b as considered above, we now assume that they have to pay for each unit of resources they acquire. We also assume that the set of firms I competing for these resources is large enough such that each firm bids competitively for the same supply of resources, i.e., they act as price takers.[6] In that case, the equilibrium price of resources, which we denote by w^*, is determined by the marginal benefit of allocating resources to either type of activities:

$$w^* \equiv \phi_y \cdot y'(b - x^*) \cdot [1 - \phi_a \cdot a(x^*)] = \phi_y \cdot y(b - x^*) \cdot \phi_a \cdot a'(x^*). \tag{5}$$

We can compare the equilibrium price of resources to what it would be in a benchmark economy that does not admit rent seeking: $\phi_y \cdot y'(b)$. We refer to this quantity as the "marginal social value of resources", since it captures an alternative benchmark in which all resources are efficiently allocated to create surplus. This benchmark also echoes the standard practice in macroeconomic growth models of abstracting from rent-seeking opportunities.

How do the resources allocated to surplus appropriation affect the marginal benefit of allocating resources to surplus creation? We have two forces going in opposite directions. First, the fact that a fraction $[1 - \phi_a \cdot a(x^*)]$ of the surplus a firm creates is appropriated by a rival firm lowers the marginal value of allocat-

[6] If the number of firms competing for the same resources was small and these firms were all rivals within the same industry, the equilibrium price of resources could be inflated by what Glode and Lowery (2016) call a "defense premium": firm i would be willing to pay a premium to outbid rival firm j and prevent it from acquiring resources that could be used to steal firm i's surplus. We shut down this strategic bidding behavior from our model since it is superfluous to our paper's key insights.

ing resources to surplus creation. Second, the fact that a firm finds it optimal to allocate resources to surplus appropriation reduces the quantity of resources allocated to surplus creation and increases their marginal benefit, $\phi_y \cdot y'(b-x^*)$, when $y(\cdot)$ is strictly concave. Overall, the existence of rent-seeking opportunities induce resources to be "overpriced" in a symmetric equilibrium whenever:

$$y'(b-x^*) \cdot [1-\phi_a \cdot a(x^*)] > y'(b).$$

This condition can only be satisfied if $y(\cdot)$ is strictly concave. The prediction that within-firm misallocation of resources can inflate the price of resources stands in contrast to the negative relationship between cross-firm misallocation and prices (see a complete discussion in Restuccia and Rogerson 2017, Dou et al. 2023, and the references therein).

2.3 Firm output

We now analyze how industry-wide technological progress affects firm output in equilibrium. While most technological progress is likely to improve the productivity of surplus creation, our analysis shows that these benefits are mitigated by firms' optimal response of shifting resources towards surplus appropriation.

Consider a technological advancement that boosts the productivity of each type of activities by $d\phi_y > 0$ and $d\phi_a > 0$, respectively. Then, equilibrium firm output, as measured by $\phi_y \cdot y(b-x^*)$, should increase by:

$$y(b-x^*) \cdot d\phi_y - \phi_y \cdot y'(b-x^*) \cdot \frac{\partial x^*}{\partial \phi_a} \cdot d\phi_a.$$

The first term in this expression captures the direct impact of increasing the productivity of surplus creation for a given equilibrium allocation of resources whereas the second term captures the indirect impact of reallocating resources towards appropriation in response to $d\phi_a$ (recall our result that ϕ_y does not affect firms' resource allocations).

The resulting increase in firm output is inferior to what it would be under the benchmark allocation without rent seeking, that is, if all resources were allocated to surplus creation: $y(b) \cdot d\phi_y$. Moreover, the wedge between the benchmark and equilibrium output levels is affected by technology parameters ϕ_y and ϕ_a in non-linear ways, as emphasized by $\frac{\partial x^*}{\partial \phi_a}$ derived in equation (4). In what follows, we parameterize the model to provide a numerical illustration in which the resource reallocation channel we study becomes so relevant that the relationship between productivity and output weakens as technology improves, even becoming negative in some cases. Indeed, technological progress causes aggregate output to further diverge from the benchmark without rent seeking that is the focus of most of the existing literature.

2.4 Numerical illustration

To illustrate our model's main insights, we parameterize the model by setting $a(x) = \frac{x}{1+x}$ and $y(s) = \frac{s}{1+s}$. The first-order condition (3) that characterizes the optimal allocation of resources in a symmetric equilibrium then becomes:

$$\frac{1}{(1+b-x^*)^2} \cdot \left[1 - \phi_a \cdot \frac{x^*}{1+x^*}\right] = \frac{b-x^*}{1+b-x^*} \cdot \phi_a \cdot \frac{1}{(1+x^*)^2},$$

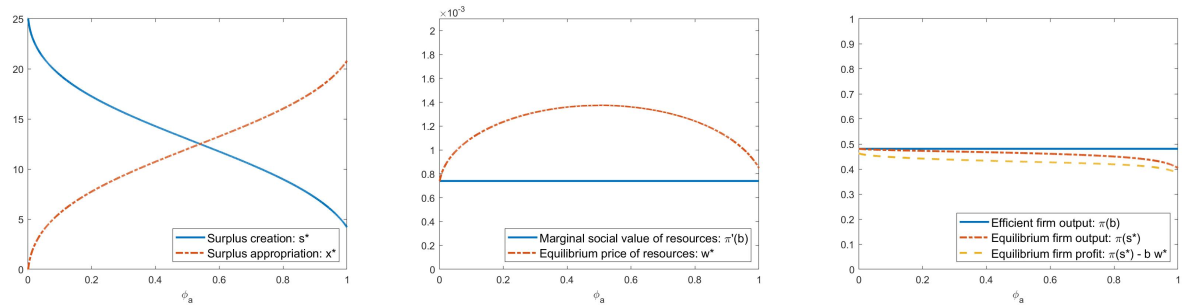
which pins down x^* as a function of the supply of resources, b, and the productivity of surplus-appropriating activities, ϕ_a. As we previously emphasized, x^* is unaffected by the productivity of surplus-creating activities, ϕ_y. The equilibrium price of resources from equation (5) is then given by:

$$w^* = \phi_y \cdot \frac{1}{(1+b-x^*)^2} \cdot \left[1 - \phi_a \cdot \frac{x^*}{1+x^*}\right] = \phi_y \cdot \frac{b-x^*}{1+b-x^*} \cdot \phi_a \cdot \frac{1}{(1+x^*)^2},$$

which does depend on the productivity of surplus-creating activities, ϕ_y.

To illustrate the impact of technological progress on resource allocation, we start with a simple scenario in which technological progress is assumed to only improve the productivity of surplus-appropriating activities. This scenario emphasizes the perverse effect of allocating resources to surplus appropriation in response to industry-wide technological progress. Later, we will extend our analysis by allowing technological progress to facilitate both surplus creation and appropriation.

Figure 1 plots, for a fixed level of ϕ_y and changing levels of ϕ_a (on the x-axis), the optimal allocation of resources, the resulting price of resources, firm output, and firm profits. Panel (a) shows that surplus appropriation is effectively shut down when $\phi_a = 0$. Hence, the intercept captures the benchmark environment without rent-seeking opportunities, in which all resources are allocated to surplus creation (i.e., $x^* = 0$ whereas $s^* = b$). As ϕ_a increases, firms start reallocating their resources towards surplus-appropriating activities. Due to the concavity of functions $y(\cdot)$ and $a(\cdot)$, the split of resources between surplus creation and



(a) Allocation of resources

(b) Price of resources

(c) Firm output/profits

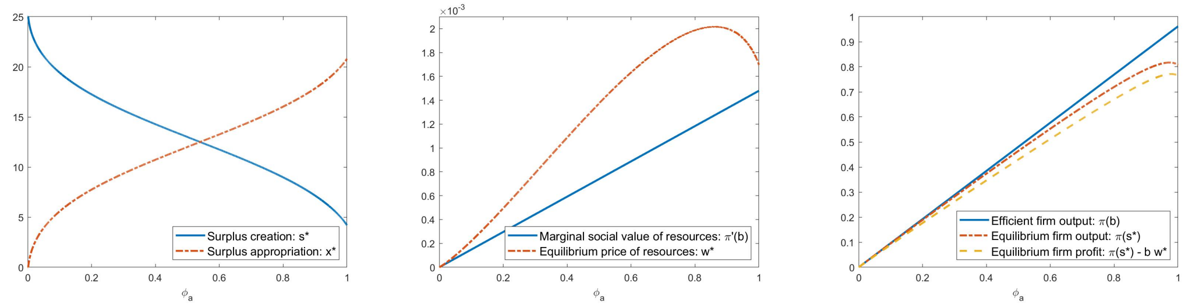
Figure 1

Impact of technological progress in surplus-appropriating activities only. The graphs illustrate how varying the productivity of surplus-appropriating activities (i.e., ϕ_a), while keeping the productivity of surplus-creating activities constant (i.e., $\phi_y = 0.5$), affects the optimal allocation of resources, the resulting price of resources, firm output and profits, when each firm gains access to a supply $b = 25$ of resources.

appropriation inflates the price that firms are willing to pay for resources (i.e., w^*) above the marginal social value of these resources (i.e., $\pi'(b)$), as shown in Panel (b). Yet, once ϕ_a gets sufficiently large, firms allocate so much of their resources to surplus appropriation that the value of those resources decline in equilibrium. The price function is then hump shaped as the price of resources reaches its maximum when the economy displays an intermediate mix of resources allocated to create as well as to appropriate surplus. Panel (c) shows that this allocation of resources leads firm output $\pi(s^*)$ to decrease and to get further away from the benchmark level of output $\pi(b)$ as we increase ϕ_a. Once we account for the high price of acquiring these resources in equilibrium, we observe that firm profits also decrease with industry-wide technological advancements that solely boost the productivity of surplus appropriation.

We now explore a richer and arguably more plausible scenario in which technological progress boosts the productivity of both types of activities: surplus creation and appropriation. In contrast with the previous exercise, this scenario allows technological progress to have a positive impact on output. Specifically, Figure 2 plots the same equilibrium objects as Figure 1, but for the case in which technology improves surplus creation and appropriation in parallel, i.e., $\phi_y = \phi_a$.

Although ϕ_y also increases, Panel (a) is identical to its counterpart from Figure 1, numerically replicating the main insight from equation (2): industry-wide technological progress in surplus creation boosts each firm's rewards from creating surplus in the same proportion as it boosts the rewards from appropriating its rival's now-larger surplus, and the firm's optimal allocation of resources remain unchanged. The marginal



(a) Allocation of resources

(b) Price of resources

(c) Firm output/profits

Figure 2

Impact of equal technological progress in both types of activities. The graphs illustrate how varying the productivity levels of surplus-appropriating activities and surplus-creating activities in parallel (i.e., $\phi_y = \phi_a$) affects the optimal allocation of resources, the resulting price of resources, firm output and profits, when each firm gains access to a supply $b = 25$ of resources.

social value of resources, however, does increase with ϕ_y, but as Panel (b) shows, the equilibrium price of resources remains inflated due to the inefficient allocation of resources to surplus-appropriating activities. As long as the resources allocated to surplus appropriation are not too large, improvements in technology yield concurrent increases in the prevalence of rent seeking and in the price firms pay for those resources. This implication casts a new light on the rising “finance wage premium” documented by Philippon and Reshef (2012) and Célérier and Vallée (2019).

Panel (c) of Figure 2 shows that equilibrium firm output benefits less from technological progress than the socially efficient level of firm output would. While our functional-form assumptions treat industry-wide technological progress as an exogenous force that linearly induces higher output, its effect is dampened by firms’ endogenous reallocation of resources towards rent seeking. This countervailing force induces concavity in the equilibrium output function and can be so dramatic that technological progress reduces firms’ output and profits.

To better understand this concavity and potential reversal, it is useful to compare the panels (c) from Figures 1 and 2. When technological progress *only* boosts the productivity of surplus appropriation, higher ϕ_a leads to more resources being allocated to appropriation and output automatically declines as a result. When technological progress instead boosts the productivity of *both* appropriation and creation in the same proportions, we still observe technological progress pushing resources to be reallocated towards surplus appropriation — the main insight of our paper. Yet, in this scenario, we have a race between two competing effects. As technology improves, fewer resources are used to create surplus, yet those resources become more productive. For low levels of $\phi_y = \phi_a$, economic output grows with technological progress: as most resources are allocated to surplus creation, the output gains from the higher productivity of surplus creation dominate the output losses from displacing resources toward surplus appropriation. For high levels of $\phi_y = \phi_a$, the resources allocated to surplus creation are so small that the output gains from the higher productivity of surplus creation become small compared to the output losses from displacing resources toward surplus appropriation. As a result, Figure 3, which zooms in on the region where $\phi_y = \phi_a \in [0.75, 1]$, shows how strong the negative impact of firms' misallocation of resources can be. In this region, the negative impact of resource misallocation dominates the positive impact of higher technological productivity on firms' output and profits. As a result, technological progress leads to lower aggregate output and profits.

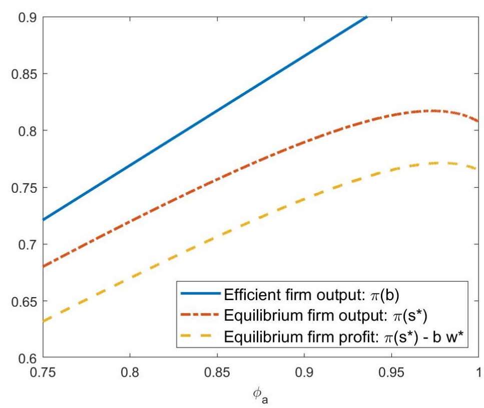


Figure 3

Non-monotonic impact of technological progress in both types of activities on firm output/profits. The graph illustrates how varying the productivity levels of surplus-appropriating activities and surplus-creating activities in parallel (i.e., $\phi_y = \phi_a$) affects firm output and profits for high productivity levels, when each firm gains access to a supply $b = 25$ of resources.

2.5 Generalized environment

In this subsection, we identify general conditions for our central prediction that technological progress leads to a reallocation of firms' resources towards surplus-appropriating activities. We also show how it is possible to reverse this prediction, yet we argue that the conditions needed to deliver our main result are realistic for most rent-seeking applications.

We can adapt our previously established notation and write firm i's profits as a general function $\Omega_i(\pi_i, \alpha_i)$

of a term that captures the output of firm i's "productive" activities, $\pi_i(s_i, \phi, S_{-i}, X_{-i})$, and a term that captures the output of firm i's "rent-seeking" activities, $\alpha_i(x_i, \phi, S_{-i}, X_{-i})$. We assume that all these functions are differentiable with respect to their arguments. We use ϕ to denote a unique parameter that captures the impact of technology on the productivity of both types of activities (yet, our general environment allows the impact of this unique ϕ to differ across activities). As before, s_i and x_i represent the resources allocated to surplus creation and appropriation, respectively, and are subject to the resource constraint $s_i + x_i \leq b_i$. We use S_{-i} and X_{-i} to denote vectors containing the resource allocations of every other firm operating in firm i's industry. This level of generality allows to broadly capture potential complementarities and spillovers across productive and rent-seeking efforts.

We now characterize firm i's best response (i.e., optimal x_i) to given levels of ϕ, S_{-i}, and X_{-i}. Imposing firm i's resource constraint, the output function for productive activities becomes $\pi_i(b_i - x_i, \phi, S_{-i}, X_{-i})$, that is, rent-seeking output is increasing in x_i and production output is decreasing in x_i. To eliminate notational clutter, whenever appropriate we dispense from the sub-index i and from the various functions' arguments and denote the partial derivative of an arbitrary function F to a variable z as $F_z \equiv \frac{\partial F}{\partial z}$. Firm i's marginal benefit from increasing the resources it allocates to rent seeking is:

$$\Omega_x = \underbrace{\Omega_\pi}_{>0} \cdot \underbrace{\pi_x}_{<0} + \underbrace{\Omega_\alpha}_{>0} \cdot \underbrace{\alpha_x}_{>0},$$

which, using $\pi_x = -\pi_s$, can be rewritten as:

$$\Omega_x = -\underbrace{\Omega_\pi}_{>0} \cdot \underbrace{\pi_s}_{>0} + \underbrace{\Omega_\alpha}_{>0} \cdot \underbrace{\alpha_x}_{>0}. \tag{6}$$

In what follows, we assume that firm i's best-response function is characterized by an interior solution to the first-order condition, that is, $\Omega_x = 0$.

Our baseline analysis implied that $\frac{\partial \Omega_x}{\partial \phi} > 0$ when technology affects both production and rent seeking proportionally — a technological improvement that equally boosted the productivity of both types of activities raised the marginal profit from moving resources from production to rent seeking. In a generalized environment, however, how does firm i's optimal x_i respond to increases in the technology parameter ϕ?

Using (6), we can write:

$$\frac{\partial \Omega_x}{\partial \phi} = -\Omega_{\pi\phi}\pi_s - \Omega_\pi \pi_{s\phi} + \Omega_{\alpha\phi}\alpha_x + \Omega_\alpha \alpha_{x\phi},$$

which, using the first-order condition $\Omega_x = 0$, can be rewritten as:

$$\frac{\partial \Omega_x}{\partial \phi} = -\Omega_\alpha \alpha_x \left[\frac{\Omega_{\pi\phi}}{\Omega_\pi} + \frac{\pi_{s\phi}}{\pi_s} - \frac{\Omega_{\alpha\phi}}{\Omega_\alpha} - \frac{\alpha_{x\phi}}{\alpha_x}\right].$$

The marginal benefit of allocating resources to rent seeking is thus increasing with technological progress as long as the term in brackets is negative, that is, as long as:

$$\frac{\Omega_{\alpha\phi}}{\Omega_\alpha} + \frac{\alpha_{x\phi}}{\alpha_x} > \frac{\Omega_{\pi\phi}}{\Omega_\pi} + \frac{\pi_{s\phi}}{\pi_s}. \tag{7}$$

The left-hand side of condition (7) measures how technological progress impacts (i) the importance of rent seeking in generating a firm's profits, and (ii) the productivity of a firm's resources allocated to rent seeking, both in proportional terms. The right-hand side of (7) measures the analog of these sensitivities for productive activities.

To interpret this general condition, we can revisit our baseline environment with $\phi_y = \phi_a \equiv \phi$ such that:

$$\Omega_i(\pi_i, \alpha_i) = \pi_i(b_i - x_i, \phi) \cdot [1 - \alpha_j(x_j, \phi)] + \alpha_i(x_i, \phi) \cdot \pi_j(b_j - x_j, \phi),$$

with $\pi(s, \phi) = \phi \cdot y(s)$ and $\alpha(x, \phi) = \phi \cdot a(x)$ for firms i and j. Using these functional forms and taking firm j's allocations x_j and s_j as given, we can write our general condition as:

$$\begin{aligned} \frac{\partial \Omega_x}{\partial \phi} &= -\phi \cdot y(s_j) \cdot \phi a'(x_i) \cdot \left[\frac{-a(x_j)}{1 - \phi \cdot a(x_j)} + \frac{y'(s_i)}{\phi \cdot y'(s_i)} - \frac{y(s_j)}{\phi \cdot y(s_j)} - \frac{a'(x_i)}{\phi \cdot a'(x_i)}\right] \\ &= \frac{\phi \cdot y(s_j) \cdot a'(x_i)}{1 - \phi \cdot a(x_j)} > 0. \end{aligned}$$

Condition (7) is thus guaranteed to hold under the standard functional forms assumed in our baseline environment. First, technological progress equally impacts the productivity of allocating an additional unit of resources to either type of activities (i.e., $\frac{\pi_{s\phi}}{\pi_s} = \frac{\alpha_{x\phi}}{\alpha_x} = \frac{1}{\phi}$). Second, technological progress does not only make a firm's profits more sensitive to its surplus-appropriating efforts (i.e., $\frac{\Omega_{\alpha\phi}}{\Omega_\alpha} = \frac{1}{\phi} > 0$) but it also makes its profits less sensitive to its surplus-creating efforts (i.e., $\frac{\Omega_{\pi\phi}}{\Omega_{\pi}} = -\frac{a(x_j)}{1-\phi a(x_j)} < 0$). As a result, resources are reallocated towards surplus appropriation in response to technological progress.

To overturn our central prediction, it would be sufficient to assume that technological progress does not affect the importance and productivity of rent seeking but increases the productivity of allocating resources to surplus creation (i.e., $\frac{\pi_{s\phi}}{\pi_s} > 0$), thereby violating condition (7) (as assumed by Murphy, Shleifer, and Vishny 1991, in a different environment). On the other hand, our mechanism gains in importance when, as in Figure 2, technological progress affects both productive and rent-seeking activities equally (or at least proportionally). Indeed, in a parameterization where $\frac{\pi_{s\phi}}{\pi_s} = \frac{\alpha_{x\phi}}{\alpha_x}$ as above, condition (7) holds if and only if:

$$\frac{\Omega_{\alpha\phi}}{\Omega_{\alpha}} > \frac{\Omega_{\pi\phi}}{\Omega_{\pi}}.$$

This simplified condition can be intuitively interpreted as follows. While output measures π_i and α_i both contribute to firm i's profits, their importance is likely to be differently impacted by technological progress. Technological improvements that can be used for rent-seeking purposes are likely to result in the surplus that a firm creates contributing less to its profits. After all, improvements in surplus-appropriation techniques should typically imply that the surplus a firm creates is less likely to be retained by that particular firm. In comparison, technological improvements that can be used for productive purposes are likely to result in making surplus-appropriating efforts more fruitful, as more surplus to appropriate should typically benefit surplus appropriators, thereby increasing the contribution of a firm's rent-seeking efforts on its profits. Our main prediction about resources being reallocated in response to technological progress relies on these economic properties of firms' profit functions, which we believe are intuitive and natural. Our generalized analysis thus shows that our main prediction can survive in arguably realistic economic settings that depart from the standard functional forms assumed in our baseline analysis.

Our generalized analysis also highlights that our main prediction ultimately stems from firms' best responses, not from our explicit equilibrium conditions. Technological progress leads to an inefficient reallocation of resources in the economy as long as condition (7) holds for all firms in the industry. This condition can hold despite the existence of large asymmetries in the functional forms of surplus creation and appropriation and regardless of the nature and split of activities between surplus creation and appropriation. In fact, we show in the next section that our main prediction holds in an environment in which subsets of firms specialize in different financial activities.

3 Application: High-Frequency Trading

The theoretical environment analyzed so far can be used to shed light on the evolution of a variety of industries that combine surplus-creating and surplus-appropriating, technology-intensive activities. One good example of that is the financial sector. It has been long recognized that many financial activities contribute to the productive allocation of resources within the economy, but also that some of its speculative activities are aimed at appropriating rather than creating surplus (see, e.g., Hirshleifer 1971, Baumol 1990, Murphy, Shleifer, and Vishny 1991, French 2008, Greenwood and Scharfstein 2013). In his Presidential Address to the American Finance Association, Zingales (2015) reflects about the growth of the financial sector as follows: *"we have both theoretical reasons and empirical evidence to claim that a component has been pure rent-seeking."* He recognizes, however, that empirically distinguishing which resources are allocated to surplus creation versus appropriation is challenging.

One technology-intensive subsector that many experts think of as featuring investments in socially inefficient activities is that of high-frequency trading (HFT) (see, e.g., Schwartz and Wu 2013, Biais, Foucault, and Moinas 2015, Budish, Cramton, and Shim 2015, Pagnotta and Philippon 2018). This subsector has grown significantly in recent decades, as can be seen in Figure 4, arguably in large part due to rapid progress in communication and computing processing technologies (see, e.g., Goldstein, Kumar, and Graves 2014, Lewis 2014, MacKenzie 2021).

Below, we describe HFT activities that are aimed at appropriating other traders' surplus such as electronic front-running, emphasize how these activities leverage technological improvements at the expense of socially beneficial activities such as market making and liquidity provision, and apply our main theoretical results to the world of HFT by extending our baseline environment along several dimensions that are relevant and specific to its operations.

3.1 Surplus creation and appropriation in an HFT context

As Adrian (2016) details, "high-frequency trading" refers to a complex collection of strategies and processes that share a few important characteristics: the use of complex computer algorithms that place orders to

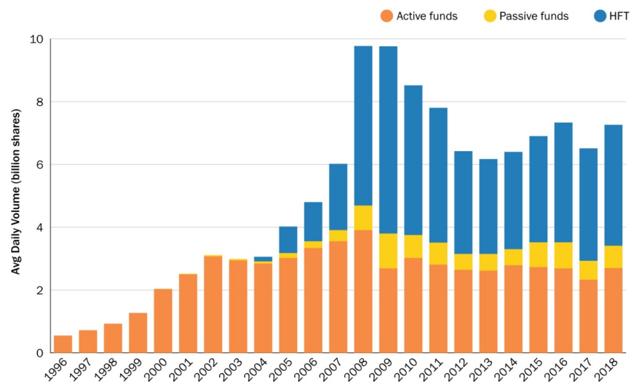


Figure 4

Growth of high-frequency trading volume. The graph plots the growth and composition of average daily trading volume in US financial markets (adapted from Klein 2020).

identify market changes, the high speed of trade execution, and the massive number of transactions executed per day. Providing an exhaustive account of all possible HFT strategies is outside the scope of our paper (see Lewis 2014, Menkveld 2016, MacKenzie 2021), but we identify and summarize two forms of trading activities that share a technological infrastructure, which has evolved at a rapid pace in recent decades and has become the platform for their operations: *market making*, which constitute a surplus-creating activity, and *electronic front-running*, a surplus-appropriating activity.

In the last couple of decades, equity trading changed dramatically. What used to happen verbally or manually in a centralized physical location (like the NYSE) now happens digitally though a network of interconnected and automated trading venues. Computing improvements and communication advances sped up the generation, routing, and execution of trade orders — some trades now being implemented within less than a millisecond (for context, the blink of an eye takes about 400 milliseconds). This astonishing reduction in trading latency had clear social benefits by helping intermediaries find trading partners and provide liquidity to their clients at unprecedented speeds.

Yet, the same technological progress has also been exploited to take advantage of transactions intended to match buyers and sellers rapidly and efficiently. Surplus created by these transactions could be appropriated by third parties designing predatory trading strategies that include rebate arbitrage, latency arbitrage, but perhaps most importantly electronic front-running. This strategy involves using speed and sophisticated computer algorithms to identify large incoming orders and take favorable positions before these large orders are fulfilled. If an institutional investor sends a large buy order to multiple exchanges, an HFT firm can learn about it from a partially unfulfilled buy request on one exchange, outrace the institutional investor's order to a second exchange and buy all available shares, in order to later resell them to the institutional investor at a higher price.[7] This strategy uses similar technology, platforms, and execution protocols to what market makers use to provide liquidity, but uses the faster speeds to step in between the ultimate buyers and sellers of assets and appropriate a fraction of their gains to trade, without generating any social surplus in the process.

Empirically, trading firms labeled as "HFT firms" have been shown to provide immediacy and liquidity to investors (see, e.g., Hendershott, Jones, and Menkveld 2011, Menkveld 2013, Korajczyk and Murphy 2018, van Kervel and Menkveld 2019) as well as to respond opportunistically to investors' large trading orders (see, e.g., Brogaard, Hendershott, and Riordan 2017, Kirilenko et al. 2017, Korajczyk and Murphy 2018, van Kervel and Menkveld 2019, Hirschey 2020). In fact, many traditional dealer banks, known to act as central market makers in various asset classes, have invested large amounts of money in order to enter the latency arms race. Goldman Sachs, for example, recently committed to invest more than $100 million to improve its equity trading technology. Reporting on this commitment for CNBC, Son (2019) writes: *"Institutional stock trading has become a winner-take-all arena in which a few big players are carving out larger slices of a shrinking pie."* Altogether, HFT firms' ambiguous contributions to financial markets and the fuzzy demarcation between market making and opportunistic trading have complicated financial regulators' optimal response to their joint creation/appropriation activities (see Gensler 2022).

To shed light on trading firms' resource allocation decisions, we next model how technological progress affects the interactions between the liquidity that trading firms provide and the electronic front-running they perform in modern financial markets.

3.2 Extended model of market making and front-running

We consider N trading firms. Each firm services a measure $Q_i(s_i)$ of clients whose liquidity needs create a social surplus $\Delta > 0$ when fulfilled. More specifically, clients who desire to sell an asset value it at $v - \Delta$,

[7] See Adrian (2016) for detailed examples of how electronic front-running is performed in practice, Menkveld (2016) for an academic survey of the related literature, and Hirschey (2020) for empirical evidence of anticipatory trading by high-frequency trading firms.

whereas clients who desire to buy the asset value it at $v+\Delta$. We can then think of v as the fundamental value of the asset. The quantity $Q_i(s_i)$ represents firm i's intermediation capacity, which is increasing in the resources s_i the firm allocates to market-making functions (e.g., hiring more personnel to deal with clients, acquiring better inventory management systems).

A trading firm provides liquidity to its clients by buying the assets they want to sell at a bid price $v-\omega\Delta$ and selling the assets they want to buy at an ask price $v+\omega\Delta$, where $\omega \in [0,1]$ captures the firm's market power, or more precisely the fraction of the social surplus the firm gets to keep as compensation for its intermediation services. A fraction $(1-\lambda)$ of the $Q_i(s_i)$ clients' transactions can be matched among themselves and therefore have no inventory consequences for the market maker. For each leg of these matched trades, the firm's profit is $\omega\Delta$. Offsetting the inventory positions associated with the remaining fraction λ of clients' transactions, either by selling an asset just acquired from a client or by buying an asset to replace inventory just sold to a client, requires the use of an electronic interdealer market.

The price that the firm faces in the interdealer market can, however, be manipulated by the $(N-1)$ other trading firms through various electronic front-running schemes. In particular, if firm j allocates resources x_j to learning about firm i's trading needs (or perhaps its clients' trading needs) fast enough, firm j can partially corner the electronic market by buying and selling assets at their fundamental value v and moving prices by $\rho_j(x_j)\cdot\Delta$ away from v, before firm i has time to completely offset its inventory positions. Altogether, the N front-running firms can move the interdealer-market price either to $v+\sum_{\substack{j=1\\j\neq i}}^{N}\rho_j(x_j)\cdot\Delta$ or to $v-\sum_{\substack{j=1\\j\neq i}}^{N}\rho_j(x_j)\cdot\Delta$, respectively based on whether firm i is looking to buy or sell in this market. The function $\rho_j(\cdot)$ is increasing to capture the notion that firm j's investments in order-flow data and in high-frequency trading platforms boost the return to front-running and other predatory trading activities. By front-running, each rival firm j appropriates a surplus $\rho_j(x_j)\cdot\Delta$ from each transaction that firm i intermediates through the interdealer market, leaving firm i with the following surplus:

$$\left[\omega-\sum_{\substack{j=1\\j\neq i}}^{N}\rho_j(x_j)\right]\Delta$$

per client transaction intermediated through the interdealer market.

If all N firms can symmetrically front-run any other firm as well as be the target of any other firm's front-running, then firm i's expected payoff can be written as:

$$Q_i(s_i) \cdot \omega\Delta \cdot \left[1 - \sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{\lambda \rho_j(x_j)}{\omega}\right] + \sum_{\substack{j=1 \\ j \neq i}}^{N} Q(s_j) \cdot \omega\Delta \cdot \frac{\lambda \rho_i(x_i)}{\omega}.$$

We thus recover a N-firm version of the profit expression (1), where $\pi_i(s_i) = Q_i(s_i) \cdot \omega\Delta$ and $\alpha_i(x_i) = \frac{\lambda \rho_i(x_i)}{\omega}$. A surplus $Q_i(s_i) \cdot \Delta$ is created by firms' provision of market-making services to clients, with the financial sector capturing a fraction ω of this surplus whereas a fraction $(1 - \omega)$ is retained by clients (thereby extending our baseline environment, where all social surplus was assumed to be captured by firms). A fraction $\lambda \rho_i(x_i)$ of the social surplus created by each firm's market making is appropriated by firm i which front-runs firms' needs to offset a fraction λ of their client transactions in an electronic interdealer market (thereby extending our baseline environment by allowing a share $(1 - \lambda)$ of the social surplus to be immune from rivals' appropriation efforts). In this setting, trading firms use their resources both for market-making and predatory-trading purposes, consistent with empirical evidence by Korajczyk and Murphy (2018), and van Kervel and Menkveld (2019), among others.

In the HFT context, it is natural to conjecture that technological investments that improve firm i's ability to front-run rival firms, such as investments in order-flow data, in computing power, in advanced algorithms and in fast trading platforms, would also contribute to making it harder for rival firms to front-run firm i. A tractable way to extend our current analysis to capture this idea is to assume that firm j's ability to appropriate firm i's surplus is a function of these firms' *relative* investments $(x_j - x_i)$ and vice-versa (see Baron et al. 2019, who document the importance of firms' *relative* latency in explaining their trading profits). Replacing $\rho_j(x_j)$ by $\rho_j(x_j - x_i)$ and using notation otherwise similar to our analysis above, we can now denote each firm's payoff as:

$$Q_i(s_i) \cdot \omega\Delta \cdot \left[1 - \sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{\lambda \rho_j(x_j - x_i)}{\omega}\right] + \sum_{\substack{j=1 \\ j \neq i}}^{N} Q_j(s_j) \cdot \omega\Delta \cdot \frac{\lambda \rho_i(x_i - x_j)}{\omega}. \tag{8}$$

While maintaining most of the same properties as our baseline analysis, this parameterization allows to additionally capture the "arms race" nature of HFT-related investments (see, e.g., Schwartz and Wu 2013, Biais, Foucault, and Moinas 2015, Budish, Cramton, and Shim 2015).

In the spirit of our baseline analysis, we can set $Q_i(s_i) \equiv \phi_y \cdot \hat{y}(s_i)$ and $\rho_i(x_i - x_j) \equiv \phi_a \cdot \hat{a}(x_i - x_j)$ to highlight the impact of industry-wide technological advancements on firms' optimal resource allocation. With regards to market making, $\hat{y}(s_i)$ captures how firm i's investments in expanding its client network and better understanding its clients' trading needs (e.g., hiring expert financial advisors and commercial bankers) translate into more intermediation volume. The technology parameter ϕ_y captures any industry-wide innovation that boosts financial firms' ability to service their clients (e.g., better telecommunication tools and social networks). With regards to front-running, $\hat{a}(x_i - x_j)$ captures how firm i's investments in speed, co-location, and order-flow data, relative to those of competing firms, translate into higher profits on the proprietary trading side of the business. The technology parameter ϕ_a captures any industry-wide innovation that boosts trading firms' ability to take advantage of their counterparties in the interdealer market (e.g., faster trading infrastructures used by electronic exchanges and increased availability of real-time order-flow data).

This parameterization of industry-wide technological progress results in the following payoff function:

$$\phi_y \hat{y}(s_i) \cdot \omega\Delta \cdot \left[1 - \sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{\lambda \phi_a \hat{a}(x_j - x_i)}{\omega}\right] + \sum_{\substack{j=1 \\ j \neq i}}^{N} \phi_y \hat{y}(s_j) \cdot \omega\Delta \cdot \frac{\lambda \phi_a \hat{a}(x_i - x_j)}{\omega}.$$

Since $b_i = s_i + x_i$, firm i's best response x_i^* to other firms' allocations can be characterized by:

$$\hat{y}(b_i - x_i^*) \cdot \sum_{\substack{j=1 \\ j \neq i}}^{N} \lambda \phi_a \hat{a}'(x_j - x_i^*) + \sum_{\substack{j=1 \\ j \neq i}}^{N} \hat{y}(b_j - x_j) \cdot \lambda \phi_a \hat{a}'(x_i^* - x_j) - \hat{y}'(b_i - x_i^*) \cdot \left[\omega - \sum_{\substack{j=1 \\ j \neq i}}^{N} \lambda \phi_a \hat{a}(x_j - x_i^*)\right] = 0.$$

As in the baseline analysis, the surplus-creation productivity ϕ_y is irrelevant for the firm's optimal allocation of resources. In contrast, a larger ϕ_a magnifies the payoff from investing in front-running activities (which include surplus protection as well as appropriation) and reduces the payoff from investing in market-making activities, and ultimately from providing liquidity to clients.

In a symmetric equilibrium with $b_i = b_j \equiv b$ and $x_i^* = x_j^* \equiv x^*$, the implicit function theorem yields:

$$\frac{\partial x^*}{\partial \phi_a} = \frac{2\hat{y}(b-x^*)\cdot\lambda\hat{a}'(0)+\hat{y}'(b-x^*)\cdot\lambda\hat{a}(0)}{2\hat{y}'(b-x^*)\cdot\lambda\phi_a\hat{a}'(0)-\hat{y}''(b-x^*)\cdot\left[\frac{\omega}{N-1}-\lambda\phi_a\hat{a}(0)\right]}.$$

This expression is strictly positive if regularity restrictions analogous to those imposed in the baseline analysis hold. Thus, as was the case in the baseline environment, any industry-wide technological advancement simultaneously boosting the productivity of market making and of electronic front-running, perhaps to different extents, will result in a reallocation of firms' resources towards front-running efforts aimed at appropriating the surplus created by others' market-making efforts.

The payoff function (8) captures the resource-allocation incentives of large sophisticated trading firms that act as market makers for clients, while also profiting from proprietary high-frequency trading.[8] We can, however, adjust this structure to study firms that participate in the market without performing both activities, such as hedge funds and HFT specialists that do not aim to create liquidity for clients, or dealer banks that specialize in market making without having an explicit HFT division.

The payoff function for hedge funds specializing in electronic front-running, without their own clienteles in need of market-making services, simplifies to:

$$\sum_{\substack{j=1\\j\neq i}}^{N} Q_j(s_j)\cdot\omega\Delta\cdot\frac{\lambda\rho_i(x_i-x_j)}{\omega} = \sum_{\substack{j=1\\j\neq i}}^{N}\phi_y\hat{y}(s_j)\cdot\Delta\cdot\lambda\phi_a\hat{a}(x_i-x_j).$$

These firms always allocate all their resources to surplus appropriation, which becomes more profitable with any increase in either ϕ_y or ϕ_a.

Consistent with the empirical findings of Brogaard et al. (2015), some trading firms specializing in market making may invest in speeding up their trading protocols as a means to defend themselves against opportunistic high-frequency traders.[9] In our environment, the payoff function for dealer banks that defend

[8] See, e.g., Stafford (2015) who describes Goldman Sachs' investment in Perseus, which at the time owned one of the fastest telecommunication connections between London and New York.

[9] Lewis (2014) describes how the Royal Bank of Canada developed THOR, a trading tool aimed at synchronizing when a large trading order reaches different exchanges, thereby weakening other firms' ability to front-run this order across exchanges.

themselves against front-running, without trying to front-run others, simplifies to:

$$Q_i(s_i) \cdot \omega\Delta \cdot \left[1 - \sum_{\substack{j=1 \\ j\neq i}}^{N} \frac{\lambda \rho_j(x_j - x_i)}{\omega}\right] = \phi_y \hat{y}(s_i) \cdot \omega\Delta \cdot \left[1 - \sum_{\substack{j=1 \\ j\neq i}}^{N} \frac{\lambda \phi_a \hat{a}(x_j - x_i)}{\omega}\right].$$

Their first-order condition when allocating resources between surplus creation and surplus protection is thus:

$$\hat{y}(b - x_i) \cdot \Delta \cdot \sum_{\substack{j=1 \\ j\neq i}}^{N} \lambda \phi_a \hat{a}'(x_j - x_i) - \hat{y}'(b - x_i) \cdot \omega\Delta \cdot \left[1 - \sum_{\substack{j=1 \\ j\neq i}}^{N} \frac{\lambda \phi_a \hat{a}(x_j - x_i)}{\omega}\right] = 0.$$

As was the case with large sophisticated trading firms involved both in surplus creation and appropriation, the technological parameter ϕ_y disappears from the firm's optimization problem, implying that technological advancements only affect the optimal allocation of resources through ϕ_a. A larger ϕ_a weakens firms' incentives to expand their surplus-creating/market-making activities and strengthens their incentives to invest in protecting their own surplus against rivals' front-running efforts, resulting in higher defense investments. As argued by Tullock (1967, 1980), investments made with the objective of defending one's surplus from rivals' appropriation efforts represent a socially wasteful allocation of scarce resources.

Altogether, a financial sector populated by these three types of firms allocates a larger share of its resources towards socially wasteful activities in response to any industry-wide technological progress that boosts productivity parameters ϕ_y and ϕ_a. These applied insights inform us on HFT firms' documented ambiguous impact on market quality: these firms provide immediacy and liquidity to investors (see, e.g., Hendershott, Jones, and Menkveld 2011, Menkveld 2013, Korajczyk and Murphy 2018, van Kervel and Menkveld 2019), yet they also respond opportunistically to investors' large trading orders (see, e.g., Brogaard, Hendershott, and Riordan 2017, Kirilenko et al. 2017, Korajczyk and Murphy 2018, van Kervel and Menkveld 2019, Hirschey 2020). These insights also shed light on why steady technological improvements in the functioning of financial markets have not lowered the average cost of financial intermediation for investors (see, e.g., Brogaard et al. 2014, Philippon 2015) and why, in some instances, speeding up an exchange's order-execution processes has paradoxically resulted in increased execution costs due to heightened adverse selection (see, e.g., Hendershott and Moulton 2011, Foucault, Kozhan, and Tham 2017).

4 Conclusion

In this paper, we show that technological advancements that improve productivity for an entire industry can generically induce a disproportionate and socially inefficient allocation of resources towards surplus-appropriating activities. Whereas industry-wide improvements in a technology used to appropriate others' surplus amplify the payoff of surplus-appropriating activities and reduce the payoff of surplus-creating activities, improvements in a technology used to create surplus amplify the payoffs of both activities in lockstep. Over time, the economy evolves towards a rent-seeking economy in response to technological progress. This long-run reallocation of resources towards surplus appropriation has important implications for the relative price of inputs as well as for the sensitivity of economic growth to technological progress.

We extend our model and apply its insights in a context of high-frequency trading. We show how industry-wide improvements in the speed of trading networks and in the availability of order flow data may result in disproportionate investments in electronic front-running and other predatory strategies, at the expense of financial firms' market-making and liquidity provision functions. This application emphasizes how trading firms' resource-allocation response to technological progress depends on their market power, their ability to match their clients' trades internally, their price impact in an interdealer market, and many other market and industry characteristics that are specific to HFT.

More broadly, our model's insights can explain the recent rise in various surplus-appropriating endeavors such as civil litigation[10], product imitation[11], government lobbying[12], and the exercise of market power[13]. These activities all share the common goal of appropriating other parties' surplus (or defending a firm's surplus from rivals' appropriation efforts). And in all these cases, we can think of recent technological advancements, whether it is big data, machine learning, artificial intelligence, communication and transportation improvements, likely to have facilitated both surplus creation and appropriation. The disproportionate effect of technological progress on rent seeking highlighted in this paper may also have been operational well before the current informational revolution. Many early technological advancements impacted both

[10] The growth in the size of the U.S. legal profession surpassed U.S. population growth since the 1940s, according to ABA (2022).

[11] The growth in patent infringement cases in the U.S. and U.K. is documented by the Council of Economic Advisers (2016) and Zhang and Qiao (2020) and the growth in counterfeit product seizures in the U.S. is documented by Snibbe (2019).

[12] The growth in lobbying is documented by Tracy (2019), OpenSecrets (2021), and Grotteria, Miller, and Naaraayanan (2023).

[13] The growth in markups for U.S. businesses is documented by De Loecker, Eeckhout and Unger (2020) and Nekarda and Ramey (2020).

surplus creation and appropriation at the same time, albeit to different extents: improvements in agricultural and farming technologies led to better nutrition as well as wars and invasions, the proliferation of weapons helped with hunting as well as stealing, and more efficient transportation technologies facilitated trading of goods but also an expansion of speculative and stealing activities.[14]

Our paper thus identifies an understudied, yet fundamental dampening effect of rent seeking on the long-run relationship between technological progress and economic progress, which points toward the heightened relevance of identifying, regulating, taxing, and/or curbing rent-seeking activities as technology improves. A salient implication of our analysis is that policies focused on boosting the productivity of surplus-creating activities from firms' standpoint (e.g., by subsidizing related investments) may backfire and have the unintended consequence of worsening the inefficient allocation of resources. Instead, policymakers must develop ways to identify the different forms of surplus appropriation and reduce their productivity in order to ultimately reduce the misallocation of resources.[15] Our results emphasize the importance of incorporating surplus appropriation as a fundamental and integral force within economic growth models and of improving its measurement for policymaking purposes. At a global level, our analysis also implies that technological progress heightens the need for societies to design coordination or commitment devices that reduce appropriation efforts (e.g., governments may implement stronger property rights, regulations and laws that curb rent seeking). The notion that more technologically developed economies are also economies with stronger institutions is thus consistent with the main implications of our paper.

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[14]Reames and Haverkost (2021) discuss the relationship between agriculture and warfare in ancient Greece, Cook and van Ludwig (2003) presents empirical evidence on the relationship between gun ownership and house burglaries, and Koudijs (2015) empirical evidence on the prevalence of insider trading through official mail packet boats in 18th-century Amsterdam.

[15]See Del Rosal (2011) for a survey of the challenges linked with identifying rent-seeking activities and their social costs.

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