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# The long-run effects of corporate tax reforms

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# The Long-Run Effects of Corporate Tax Reforms*

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**Abstract**

We investigate the long-run effects of permanent corporate tax reforms on aggregate capital behavior. In an investment model with fixed adjustment costs and partial irreversibility, we show that corporate taxes and investment frictions jointly determine three interconnected macroeconomic outcomes: (i) capital allocation, (ii) capital valuation, and (iii) capital fluctuations around steady-state. Using corporate tax and firm-level investment data from Chile, we discover that a lower corporate income tax improves the allocation of capital, reduces capital valuation, and accelerates capital fluctuations.

**JEL**: D30, D80, E20, E30

**Keywords**: corporate taxes, investment frictions, fixed adjustment costs, irreversibility, lumpiness, capital misallocation, Tobin's $q$, transitional dynamics, inaction, propagation.

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# 1 Introduction

Corporate tax reforms are back in the spotlight. Current economic developments—massive government debts accumulated to finance the recovery from the COVID-19 pandemic, heightened tax competition for foreign direct investment, and a secular increase in business profits—have revived the interest in corporate taxation among policymakers and academics. Since addressing these issues will likely require persistent changes in countries' corporate tax structures, which in turn will structurally change private investment behavior, it is critical to understand and quantify the long-run macroeconomic effects that these reforms may bring.

We study the effects of permanent corporate tax reforms on the long-run behavior of aggregate capital: its allocation across firms, its market valuation, and its fluctuations around steady-state. We develop a parsimonious investment model with firm heterogeneity, empirically-relevant investment frictions, including a fixed capital adjustment cost (Caballero and Engel, 1999) and a wedge between the purchase and resale prices of capital that makes investment partially irreversible (Abel and Eberly, 1996), and a comprehensive corporate tax schedule (Summers, 1981; Abel, 1982). Our model's tax schedule includes a corporate income tax, a personal income tax, a capital gains tax, and depreciation deductions. This environment enables us to formalize the mechanisms through which the interaction of corporate taxes and investment frictions distort the allocation of capital across firms, and in turn, how the capital allocation shape its valuation and fluctuations.

We offer three new insights. First, corporate taxes affect aggregate capital behavior through two distinct channels: (i) a neoclassical frictionless user-cost channel, which determines the steady-state *level* of capital, and (ii) a frictional dynamic optimization channel, which shapes the *allocation* of capital across firms. Specifically, we show that *after-tax investment frictions*—namely, the fixed cost relative to the after-tax frictionless profits and the price wedge relative to the after-tax frictionless profit-capital ratio—are the key objects affecting dynamic investment decisions. For instance, reducing the corporate income tax rate raises frictionless profits and thus decreases firms' effective fixed costs. These results imply that, up to re-scaling, an economy with corporate taxes is isomorphic to an economy without them. Consequently, in order to assess the dynamic effects of taxation, one needs only to understand the role of investment frictions.

Our second insight is that *capital misallocation*, defined as the cross-sectional dispersion in log marginal revenue products (Hsieh and Klenow, 2009; Restuccia and Rogerson, 2013) and proportional to the dispersion of capital-productivity ratios, is the common driver behind capital valuation and capital fluctuations.[1] We measure *capital valuation* as the capital-weighted average of individual Tobin's marginal $q$. And following Álvarez and Lippi (2014), we measure *capital fluctuations* around steady-state as the cumulative impulse response (CIR) to an unanticipated

[1]In our setup, dispersion in marginal products arises exclusively due to dynamic input optimization under adjustment frictions. This assumption is consistent with Asker, Collard-Wexler and De Loecker (2014) who show that adjustment costs have a predominant role in shaping the dispersion of static measures of capital misallocation.

small shock to aggregate productivity.[2] We show analytically that aggregate $q$ decreases with capital misallocation, the average capital-productivity ratio, and the price wedge. In contrast, we show that the CIR increases with capital misallocation, the relative cost of downsizing vs. upsizing the capital stock, and the price wedge. Together, these results suggest that an economy with lower after-tax investment frictions—which manifest in lower capital misallocation—feature higher asset valuations (higher $q$) and faster propagation of productivity shocks (smaller CIR) if the relative strength of the misallocation channel dominates other forces.

Our third insight is that a few observable micro-moments of the joint distribution of investment and duration of inaction spells encode the distinct forces that shape capital behavior. These moments are easily computed in microdata panels and serve two purposes. First, they disentangle the separate roles of fixed costs and price wedges in generating misallocation. Disentangling the role of each friction is a necessary step in understanding the effects of corporate tax reforms, as each friction interacts differently with each tax instrument (for instance, we show that the corporate income tax affects the fixed cost but not the price wedge). Second, these micro-moments serve as sufficient statistics for measuring capital misallocation, $q$, and the CIR, and thus predict the direction in which the aggregate capital measures will move after a tax reform by looking at the changes in these micro moments. The main advantage of our approach is that it only uses investment data. To the extent that revenues are noisier than investment, for example, due to measurement error or transitory shocks, our "micro-moments" approach provides researchers with a suitable alternative to estimating capital misallocation.

We apply these three insights to examine the macroeconomic consequences of a regime shift from high to low corporate taxes. We focus on changes to the top marginal corporate income tax rate, which showed a median decrease of 17 percentage points from 42% in 1980 to 25% in 2020 across OECD countries.[3] According to our theory, a decline in the corporate income tax rate is equivalent to a reduction in the after-tax fixed cost. While this decline should unambiguously reduce misallocation, the effects on valuation and fluctuations depend on the magnitude of other forces, which in turn, rest on the size of investment frictions.

We discipline investment frictions by matching the model-consistent micro-moments from Chilean investment data.[4] Using the calibrated model, we examine the elasticity of aggregate capital measures to the corporate income tax. Our results suggest that, other things equal, a

[2]The CIR summarizes the impact and persistence of the economy's response in one scalar, which represents a multiplier of aggregate shocks. A higher CIR implies slower propagation and larger effects of the aggregate shock. Álvarez, Le Bihan and Lippi (2016), Baley and Blanco (2019), Álvarez, Lippi and Oskolkov (2020), and Alexandrov (2021) use the CIR in the context of price-setting models to assess the effects of monetary shocks.

[3]While the median corporate income tax rate has continuously decreased during this period, reforms at the country level are very infrequent. In the US, for instance, only four reforms occurred in the last 40 years. The US statutory federal corporate tax rate was 46% from 1979-1986, 40% in 1987, 34% from 1988-1993, 35% from 1994-2017, and has been 21% since 2018. See Data Appendix E.

[4]The Chilean context and establishment-level data have various advantages to study changes in the corporate income tax rate, as we explain in Section 5.

lower corporate income tax rate decreases capital misallocation across tax regimes. It also reduces the CIR so that the propagation of aggregate productivity shocks accelerates. Surprisingly, we find that a lower corporate income tax rate decreases capital valuation. On the one hand, lower taxes reduce misallocation, which increases $q$; on the other hand, lower taxes raise the average level of capital, which decreases $q$. We find that the second effect dominates quantitatively.

In summary, we propose a laboratory for examining the macroeconomic effects of permanent corporate tax reforms focusing on the interaction of taxes with investment frictions. Our analysis puts forward a new channel for policy intervention. Corporate tax policy can change the effective size of fixed costs or irreversibility wedges—technological constraints or market prices typically outside the control of a policymaker—and structurally change the steady-state behavior of aggregate capital and the macroeconomy more broadly.

**Contributions to the literature.** The long-run effects of permanent corporate tax reforms on aggregate capital have been widely studied. Early contributions (Summers, 1981; Abel, 1982; Poterba and Summers, 1983; King and Fullerton, 1984; Auerbach, 1986; Auerbach and Hines, 1986), and more recently Barro and Furman (2018), used a neoclassical model with a representative firm suitable to understand the user-cost channel of taxation. Subsequent work incorporated firm heterogeneity and non-convex adjustment costs (Miao, 2019; Gourio and Miao, 2010; Miao and Wang, 2014) to investigate the frictional dynamic channel of taxation. We contribute showing how to reduce the complex interactions between corporate taxes and investment frictions to a rescaling of the appropriate friction. This idea considerably simplifies the analysis and highlights the channels through which corporate tax reforms affect private investment.

We also contribute to the literature investigating the short-run stimulus of corporate tax policy on average investment (see Hall and Jorgenson, 1967, for early work). Within this literature, our work is closely related to the structural frameworks in Winberry (2021), who studied the stimulus effects of bonus depreciation in the US, and to Chen, Jiang, Liu, Suárez Serrato and Xu (2019), who studied the stimulus effects of the 2009 VAT reform in China.[5] As corporate tax policies often exhibit high persistence, our study of permanent tax reforms directly complements previous research on short-run stimulus effects. Additionally, we derive predictions for new dimensions of capital behavior (misallocation, valuation, and fluctuations), characterize the mechanisms that shape them, and show how to tighten calibrations with microdata.

Finally, we contribute to the literature studying the role of micro-level adjustment frictions for economic fluctuations (see Caplin and Spulber, 1987; Caballero and Engel, 1991, 1993, for early contributions). Recent work identifies a small set of observable micro-moments that capture the

[5]Other work assessing the short-run stimulating role of different corporate tax policies, from an applied public finance perspective, includes Hassett and Hubbard (2002); House and Shapiro (2008); Yagan (2015); Zwick and Mahon (2017); Ohrn (2018); Boissel and Matray (2019); Maffini, Xing and Devereux (2019) and Lerche (2019). More recently, Rotemberg (2019) and Aneja, Kulkarni and Ritadhi (2021) study the effects of corporate tax reforms on misallocation and productivity.

role of adjustment frictions for the propagation of aggregate shocks (see Álvarez, Le Bihan and Lippi, 2016; Baley and Blanco, 2021). We contribute to this line of work in three ways. First, we consider the role of corporate taxes in shaping the observable micro-moments. Second, we characterize additional macroeconomic outcomes, such as aggregate $q$, with a few micro-statistics. Third, we show how to handle history dependence (or reinjection, as labeled by Álvarez and Lippi, 2021) arising from partial irreversibility to generate mappings from microdata to aggregate outcomes. In this way, we expand the breadth of the micro-moments methodology to the realm of models with irreversibility (Bertola and Caballero, 1994; Abel and Eberly, 1996; Ramey and Shapiro, 2001; Veracierto, 2002; Lanteri, 2018; Lanteri, Medina and Tan, 2020) and other sources of history dependence.

# 2 Investment With Fixed Costs and a Price Wedge

In this section, we develop a parsimonious investment model with the following features: idiosyncratic productivity shocks, fixed capital adjustment costs, a wedge between the purchase and resale prices of capital, and a constant interest rate.

## 2.1 The problem of an individual firm

Time is continuous, extends forever, and it is denoted by $s$. The future is discounted at rate $\rho > 0$. We first present the problem of an individual firm and then consider a continuum of ex-ante identical firms to characterize the aggregate behavior of the economy.

**Technology and shocks.** The firm produces output $y_s$ using capital $k_s$ according to a production function with decreasing returns to scale

$$y_s = u_s^{1-\alpha} k_s^{\alpha}, \quad \alpha < 1. \tag{1}$$

Flow profits equal $\pi_s \equiv A y_s$, where $A > 0$ is a profitability parameter. Idiosyncratic productivity $u_s$ follows a geometric Brownian motion with drift $\mu > 0$ and volatility $\sigma > 0$,

$$\log u_s = \log u_0 + \mu s + \sigma W_s, \qquad W_s \sim Wiener. \tag{2}$$

The capital stock, if uncontrolled, depreciates at rate $\xi^k > 0$.

**Investment frictions.** The firm can control its capital stock through buying and selling investment goods at prices $p^{\text{buy}}$ and $p^{\text{sell}}$. We assume an exogenous price wedge $p^{\text{buy}} - p^{\text{sell}} > 0$ which reflects adverse selection, specificity of capital goods, or other frictions in the market for used capital that make investment partially irreversible.[6] For every investment $i_s \equiv \Delta k_s = k_s - k_{s^-}$, the firm must pay an adjustment cost proportional to its productivity $\theta_s = \theta u_s$, where $\theta > 0$ is constant and it is measured in consumption units.[7] To simplify notation, we define the price function

$$p(i_s) \;=\; p^{\text{buy}} \mathbb{1}_{\{i_s>0\}} + p^{\text{sell}} \mathbb{1}_{\{i_s<0\}}. \tag{3}$$

**Investment problem.** Let $V(k,u)$ denote the value of a firm with capital stock $k$ and productivity $u$. Given initial conditions $(k_0,u_0)$, the firm chooses a sequence of adjustment dates $\{T_h\}_{h=1}^{\infty}$ and investments $\{i_{T_h}\}_{h=1}^{\infty}$, where $h$ counts the number of adjustments, to maximize its expected discounted stream of profits. The sequential problem is

$$V(k_0,u_0) \;=\; \max_{\{T_h, i_{T_h}\}_{h=1}^{\infty}} \mathbb{E}\left[\int_0^{\infty} e^{-\rho s}\pi_s \,\mathrm{d}s - \sum_{h=1}^{\infty} e^{-\rho T_h}\left(\theta_{T_h} + p\left(i_{T_h}\right) i_{T_h}\right)\right], \tag{4}$$

subject to the production technology (1), the idiosyncratic productivity shocks (2), the investment price function (3), and the law of motion for the capital stock

$$\log k_s \;=\; \log k_0 - \xi^k s + \sum_{h:T_h\le s}\left(1 + i_{T_h}/k_{T_h^-}\right), \tag{5}$$

which describes a period's capital as a function of its initial value $k_0$, the physical depreciation rate $\xi^k$, and the sum of all adjustments made at prior adjustment dates.

## 2.2 Capital-productivity ratios $\hat{k}$

To characterize the investment decision, it is convenient to reduce the state-space and recast the firm problem using a new state variable, the log capital-productivity ratio:

$$\hat{k}_s \;\equiv\; \log\left(k_s/u_s\right). \tag{6}$$

The problem admits this reformulation because the production function is homothetic and the adjustment costs are proportional to productivity[8]. Note that in the absence of investment frictions, $\hat{k}_s$ is a constant. With investment frictions, between any two consecutive adjustment dates

[6] Lanteri (2018) endogenizes the price wedge in the market of used capital goods. Additional tax-related sources of a price wedge include non-deductible VAT tax (Chen, Jiang, Liu, Suárez Serrato and Xu, 2019) and investment tax credits (Altug, Demers and Demers, 2009).

[7] For any stochastic process $q_s$, we use the notation $q_{s^-} \equiv \lim_{r\uparrow s} q_r$ to denote the limit from the left.

[8] We can also reformulate the problem using the capital-productivity ratio assuming that adjustment costs scale with output or the capital stock.

$[T_{h-1}, T_h]$, the capital-productivity ratio $\hat{k}$ follows a Brownian motion

$$d\hat{k}_s = -\nu \, ds + \sigma \, dW_s, \tag{7}$$

where the drift $\nu \equiv \xi^k + \mu$ reflects the depreciation rate and productivity growth rate. At any adjustment date $T_h$, the log capital-productivity ratio changes by the amount

$$\Delta \hat{k}_{T_h} = \log\left(1 + i_{T_h}/k_{T_h^-}\right). \tag{8}$$

Using the Principle of Optimality, Lemma 1 rewrites the sequential problem in (4) as a recursive stopping-time problem. It also shows that the value of the firm equals a function of the log capital-productivity ratio $\hat{k}$ that scales with productivity, that is, $V(k,u) = uv(\hat{k})$. Since $\Delta\hat{k}_s$ and $i_s$ have the same sign, we write the investment price as $p(\Delta\hat{k})$. All proofs appear in Appendix A.

**Lemma 1.** *Let $r \equiv \rho - \mu - \sigma^2/2$ be the adjusted discount factor and let $v(\hat{k}) : \mathbb{R} \to \mathbb{R}$ be a function of the log capital-productivity ratio equal to*

$$v(\hat{k}) = \max_{\tau, \Delta\hat{k}} \mathbb{E}\left[\int_0^\tau A e^{-rs + \alpha \hat{k}_s} \, ds + e^{-r\tau}\left(-\theta - p(\Delta\hat{k})(e^{\hat{k}_\tau + \Delta\hat{k}} - e^{\hat{k}_\tau}) + v(\hat{k}_\tau + \Delta\hat{k})\right) \Big| \hat{k}_0 = \hat{k}\right]. \tag{9}$$

*Then the firm value equals $V(k,u) = uv(\hat{k})$.*

### 2.3 Optimal investment policy

The optimal investment policy is characterized by four numbers, $\mathcal{K} \equiv \{\hat{k}^- \leq \hat{k}^{*-} \leq \hat{k}^{*+} \leq k^+\}$, which correspond to the lower and upper borders of the inaction region

$$\mathcal{R} = \left\{\hat{k} : \hat{k}^- < \hat{k} < \hat{k}^+\right\}, \tag{10}$$

and two reset points $\hat{k}^{*-} < \hat{k}^{*+}$. A firm adjusts if and only if its log capital-productivity ratio falls outside the inaction region, that is, $\hat{k}_s \notin \mathcal{R}$. Conditional on adjusting, the firm purchases capital to bring its state up to $\hat{k}^{*-}$ if it hits the lower border $\hat{k}^-$, and sells capital to bring its state down to $\hat{k}^{*+}$ if it hits the upper border $\hat{k}^+$. Given $\mathcal{R}$, the optimal adjustment dates are

$$T_h = \inf\left\{s \geq T_{h-1} : \hat{k}_s \notin \mathcal{R}\right\} \quad \text{with} \quad T_0 = 0. \tag{11}$$

The duration of a complete inaction spell $\tau_h$ and the time elapsed since the last adjustment $a_s$ (or the age of the capital-productivity ratio) are

$$\tau_h = T_h - T_{h-1}, \tag{12}$$

$$a_s = s - \max\{T_h : T_h \leq s\}. \tag{13}$$

To save on notation, we write the reset points and the stopped capitals (an instant before adjustment) as functions of the adjustment sign:

$$\hat{k}^*(\Delta\hat{k}) = \begin{cases} \hat{k}^{*-} & \text{if} \quad \Delta\hat{k} > 0 \\ \hat{k}^{*+} & \text{if} \quad \Delta\hat{k} < 0, \end{cases} \tag{14}$$

$$\hat{k}_\tau(\Delta\hat{k}) = \hat{k}^*(\Delta\hat{k}) - \Delta\hat{k}. \tag{15}$$

Lemma 2 characterizes the value function and the optimal investment policy through the standard sufficient optimality conditions. The firm value and the policy must satisfy: (i) the Hamilton-Jacobi-Bellman equation in (16), which describes the evolution of the firm's value during periods of inaction, (ii) the value-matching conditions in (17) and (18), which set the value of adjusting equal to the value of not adjusting at the borders of the inaction region, and (iii) the smooth-pasting and optimality conditions in (19) and (20), which ensure differentiability at the borders of inaction and the two reset points.

**Lemma 2.** *The value function $v(\hat{k})$ and the optimal policy $\mathcal{K} \equiv \{\hat{k}^-, \hat{k}^{*-}, \hat{k}^{*+}, \hat{k}^+\}$ satisfy:*

*(i) In the inaction region $\mathcal{R}$, $v(\hat{k})$ solves the HJB equation:*

$$rv(\hat{k}) = Ae^{\alpha\hat{k}} - \nu v'(\hat{k}) + \frac{\sigma^2}{2}v''(\hat{k}). \tag{16}$$

*(ii) At the borders of the inaction region, $v(\hat{k})$ satisfies the value-matching conditions:*

$$v(\hat{k}^-) = v(\hat{k}^{*-}) - \theta - p^{buy}(e^{\hat{k}^{*-}} - e^{\hat{k}^-}), \tag{17}$$

$$v(\hat{k}^+) = v(\hat{k}^{*+}) - \theta + p^{sell}(e^{\hat{k}^+} - e^{\hat{k}^{*+}}). \tag{18}$$

*(iii) At the borders of the inaction region and the two reset states, $v(\hat{k})$ satisfies the smooth-pasting and the optimality conditions:*

$$v'(\hat{k}) = p^{buy}e^{\hat{k}}, \quad \hat{k} \in \left\{\hat{k}^-, \hat{k}^{*-}\right\}, \tag{19}$$

$$v'(\hat{k}) = p^{sell}e^{\hat{k}}, \quad \hat{k} \in \left\{\hat{k}^{*+}, \hat{k}^+\right\}. \tag{20}$$

*The optimal policy in terms of capital is recovered as* $\{k^-, k^{*-}, k^{*+}, k^+\} = u \times \exp\{\hat{k}^-, \hat{k}^{*-}, k^{*+}, k^+\}$.

## 2.4 Individual Tobin's $q$

Next, we express the optimal investment decision using Tobin's $q$, namely, the shadow price of installed capital. Following Abel and Eberly (1994), we identify a firm's Tobin's $q$ as the marginal valuation of an extra unit of installed capital, which is equal to

$$q(\hat{k}) \equiv \frac{\partial V(k,u)}{\partial k} = v'(\hat{k})e^{-\hat{k}}. \tag{21}$$

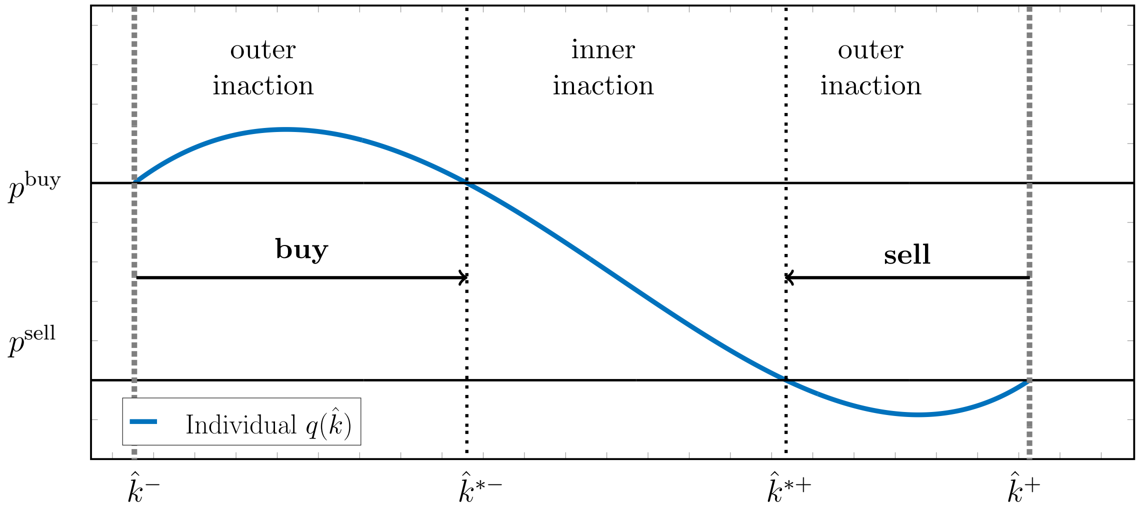
In contrast to its standard definition, the replacement cost of capital (the investment price) does not divide Tobin's $q$ in (21). The reason is that, with partial irreversibility, the price depends on the direction of the next adjustment. Thus, it varies depending on the position of $\hat{k}$.

Figure I describes the optimal investment policy using $q(\hat{k})$. Moreover, we can use this diagram to describe how each investment friction affects the firm's optimal policy. Let's consider first an environment with partial irreversibility and no fixed costs. Without the fixed adjustment cost ($\theta = 0$), a firm purchases capital if $q(\hat{k}) \geq p^{\text{buy}}$ (or $\hat{k} \leq \hat{k}^{*-}$) and sells capital if $q(\hat{k}) \leq p^{\text{sell}}$ (or $\hat{k} \geq \hat{k}^{*+}$) without any delay. When $q(\hat{k})$ lies between the two prices (or the state between the two reset points), it is optimal to remain inactive. At that productivity level, it is too expensive to purchase capital and too cheap to sell it. This gives rise to an "inner" inaction region $[\hat{k}^{*-}, \hat{k}^{*+}]$ due exclusively to partial irreversibility. Next, let's consider an environment with fixed costs and no partial irreversibility. Without a price wedge ($p^{\text{buy}} = p^{\text{sell}}$), the "inner" inaction region collapses to a unique reset point $k^*$. However, the fixed adjustment cost generates an "outer" inaction region $[\hat{k}^-, \hat{k}^+]$ that prevents firms from adjusting, even if $q(\hat{k})$ lies above or below the investment price. When both frictions are active, the policy features both "outer" and "inner" inaction regions and two reset points.

The interaction of the investment frictions generates two interesting features in the optimal investment behavior. First, as argued by Caballero and Leahy (1996), individual $q(\hat{k})$ is *not monotonic* in $\hat{k}$. Without fixed costs, $q(\hat{k})$ monotonically decreases with $\hat{k}$ due to decreasing returns to scale $\alpha < 1$. With fixed costs, however, firms anticipate large adjustments when approaching the inaction thresholds. As $\hat{k}$ approaches the lower threshold $\hat{k}^-$, firms anticipate that a future tiny change in the state $\mathrm{d}\hat{k} < 0$ will trigger a large positive adjustment $\Delta\hat{k} > 0$. The future positive investment lowers future $q(\hat{k})$ and feeds back into lower current $q(\hat{k})$, bending down the function. A reverse argument explains why $q(\hat{k})$ bends up as $\hat{k}$ approaches the upper threshold $\hat{k}^+$. As a result, individual $q(\hat{k})$ is *not a sufficient statistic for individual investment*, in contrast to the postulate in Tobin (1969).

Second, optimal investment features an *endogenous positive serial correlation in the sign of adjustments*. A firm is more likely to buy capital if it bought capital recently, and it is more

**Figure I** – Optimal Investment Policy




Notes: The figure plots the individual $q(\hat{k}) = v'(\hat{k})/e^{\hat{k}}$ and the investment policy $\mathcal{K} = \{\hat{k}^-, \hat{k}^{*-}, \hat{k}^{*+}, \hat{k}^+\}$.

likely to sell capital if it sold capital recently. This correlation arises because the inner inaction region generated by the price wedge widens the distance between the two borders of inaction but shortens the distance between each border of inaction and its corresponding reset point. Thus, it is more likely to reach $\hat{k}^-$ from the nearby $\hat{k}^{*-}$ than from the further $\hat{k}^{*+}$. The serial correlation in adjustment sign generates history dependence, which is technically challenging. Below, we show how to handle history dependence with distributions conditional on the last reset point.

## 2.5 Economy with a continuum of firms

Consider an economy populated by a continuum of ex ante identical firms that face the investment problem from the previous section. Idiosyncratic shocks $W_s$ are independent across firms. As a result, the economy features stationary cross-sectional distributions of capital-productivity ratios and investment. Here, we define and discuss the characteristics of these distributions to build intuition for the results in later sections. The analytical characterization of the macroeconomic outcomes and the mappings to the microdata derived in Section 3 hinge completely on how we deal with partial irreversibility when characterizing the cross-sectional behavior of the economy. Specifically, our strategy consists of *conditioning on the last reset point* and using relative frequencies of upward and downward adjustment to back out the unconditional behavior.

**Distribution of firms.** Let $G(\hat{k})$ be the distribution of firms over their log capital-productivity ratio and let $g(\hat{k})$ be its continuous marginal density. Also, let $\mathcal{N}^-$, $\mathcal{N}^+$, and $\mathcal{N} = \mathcal{N}^- + \mathcal{N}^+$ be the frequencies of positive, negative, and non-zero adjustments in the *total population*, which are equal to the mass of firms that adjust to $\hat{k}^{*-}$, to $\hat{k}^{*+}$, or to either point.[9] The density and frequencies solve the following system, which includes: a Kolmogorov forward equation that describes the evolution of capital-productivity ratios inside the inaction region (excluding the two reset points)

$$\nu g'(\hat{k}) \;+\; \frac{\sigma^2}{2} g''(\hat{k}) \;=\; 0, \quad \text{for all} \quad \hat{k} \in (\hat{k}^-, \hat{k}^+) \setminus \{\hat{k}^{*-}, \hat{k}^{*+}\}; \tag{22}$$

three border conditions

$$g(\hat{k}) \;=\; 0, \quad \text{for} \;\; \hat{k} \in \{\hat{k}^{*-}, \hat{k}^{*+}\}, \tag{23}$$

$$\int_{\hat{k}^-}^{\hat{k}^+} g(\hat{k})\, \mathrm{d}\hat{k} \;=\; 1; \tag{24}$$

two resetting conditions

$$\underbrace{\frac{\sigma^2}{2} \lim_{\hat{k} \downarrow \hat{k}^-} g'(\hat{k})}_{\mathcal{N}^-} \;=\; \frac{\sigma^2}{2} \left[ \lim_{\hat{k} \uparrow \hat{k}^{*-}} g'(\hat{k}) - \lim_{\hat{k} \downarrow \hat{k}^{*-}} g'(\hat{k}) \right], \tag{25}$$

$$\underbrace{-\frac{\sigma^2}{2} \lim_{\hat{k} \uparrow \hat{k}^+} g'(\hat{k})}_{\mathcal{N}^+} \;=\; \frac{\sigma^2}{2} \left[ \lim_{\hat{k} \uparrow \hat{k}^{*+}} g'(\hat{k}) - \lim_{\hat{k} \downarrow \hat{k}^{*+}} g'(\hat{k}) \right], \tag{26}$$

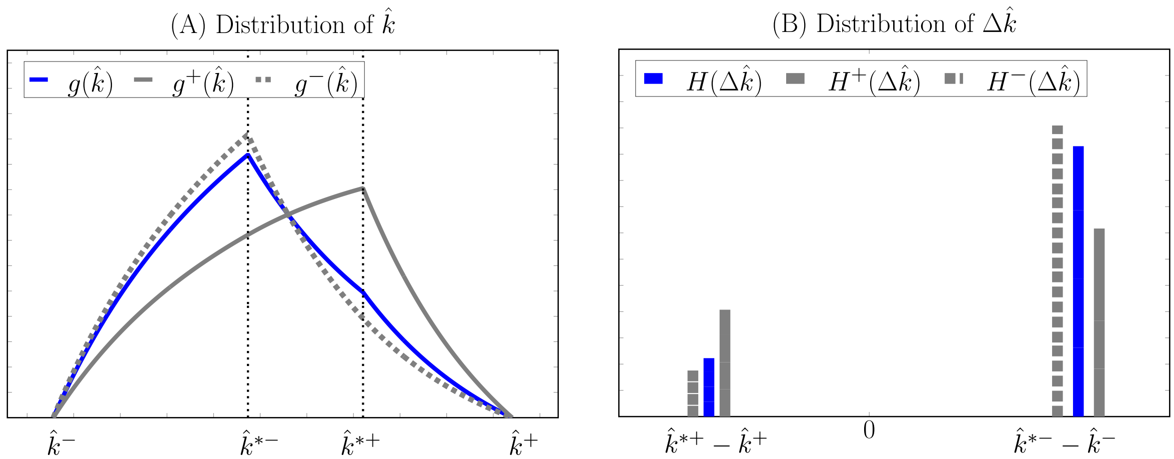
and two continuity conditions at the reset points (not reported). Condition (23) sets the mass of firms at the inaction thresholds equal to zero. Condition (24) ensures that $g$ is a density. Conditions (25) and (26) relate the masses of upward and downward adjustments to the discontinuities in the derivative of $g$ at the reset points. In a small period of time $\mathrm{d}s$, the mass $\mathcal{N}^-$ that "exits" the inaction region by hitting the lower threshold—equal to $\frac{\sigma^2}{2} \lim_{\hat{k} \downarrow \hat{k}^-} g'(\hat{k})$—must coincide with the mass of firms that "enters" at the reset point $\hat{k}^{*-}$—equal to the jump in $g'$. This argument is analogous for $\mathcal{N}^+$; in fact, it is straightforward to verify that conditions (22) to (25) jointly imply condition (26), and thus it is redundant.

To handle the history dependence that manifests in the autocorrelation of the investment sign, we define densities *conditional on the last reset point*. We let $g^-(\hat{k})$ and $g^+(\hat{k})$ denote the stationary density of $\hat{k}$ conditional on the last reset point being $\hat{k}^{*-}$ or $\hat{k}^{*+}$, respectively. In particular, $g^-$ satisfies the same KFE in (22) for all $\hat{k} \in (\hat{k}^-, \hat{k}^+) \setminus \hat{k}^{*-}$ (there is no entry at $\hat{k}^{*+}$), the border conditions (23) and (24), and continuity at $\hat{k}^{*-}$.[10] An analogous characterization applies to $g^+$. Panel A in Figure II plots the three densities $g$, $g^-$ and $g^+$ (these are proper densities and integrate to 1). We denote expectations computed with these distributions as $\mathbb{E}$, $\mathbb{E}^-$, and $\mathbb{E}^+$.

[9] To avoid any confusion with our notation, we emphasize that the sign in the exponent of an object refers to the last reset point, not to the sign of the adjustment.

[10] Besides the border conditions, there is one reseting condition relating the mass of adjusters to the unique discontinuity in the derivative of $g^-$, but it is implied by the border conditions.

**Figure II** – Unconditional and Conditional Distributions of $\hat{k}$ and $\Delta\hat{k}$




Notes: Panel A plots the unconditional density $g(\hat{k})$ and the densities conditional on the last reset $g^{\pm}(\hat{k})$. Panel B plots the unconditional distribution $H(\Delta\hat{k})$ and the distributions conditional on the last reset $H^{\pm}(\Delta\hat{k})$.

**Distributions of actions.** Next, we consider the distribution over actions—adjustment size and the duration of inaction—denoted by $H(\Delta\hat{k}, \tau)$, and the distributions of actions *conditional on the last reset point*: $H^-(\Delta\hat{k}, \tau)$ and $H^+(\Delta\hat{k}, \tau)$. Panel B of Figure II plots the marginal distributions of adjustment size, $H(\Delta\hat{k})$, $H^-(\Delta\hat{k})$, $H^+(\Delta\hat{k})$, where we have integrated out the duration $\tau$; these distributions correspond to probability masses at two points $\Delta\hat{k} = \hat{k}^{*+} - \hat{k}^+ < 0$ and $\Delta\hat{k} = \hat{k}^{*-} - \hat{k}^- > 0$. We denote with bars the expectations computed with the distributions of adjusters: $\overline{\mathbb{E}}$, $\overline{\mathbb{E}}^-$ and $\overline{\mathbb{E}}^+$.

Panel B in Figure II illustrates two key characteristics of the distribution of adjustments. First, the mass of upward adjustments $H(\hat{k}^{*-} - \hat{k}^-)$ is larger than the mass of downward adjustments $H(\hat{k}^{*+} - \hat{k}^+)$. This is because the drift shrinks capital-productivity ratios over time prompting upward adjustments and because partial irreversibility penalizes downward adjustments. This asymmetry is also observed in the firms' distribution, as $g$ is closer to $g^-$. Second, the conditional masses reflect the autocorrelation in the investment sign; for instance, $H^- > H^+$ at $\Delta\hat{k} > 0$ means that the probability of reseting to $\hat{k}^{*-}$ is larger whenever the last reset point was also $\hat{k}^{*-}$. In other words, positive investments beget future positive investments.

**From conditional to unconditional distributions.** Define the shares of upward $\mathcal{N}^-/\mathcal{N}$ and downward $\mathcal{N}^+/\mathcal{N}$ adjustments within the *population of adjusters*. By Bayes' law, the unconditional and conditional distribution of adjusters satisfy

$$H(\Delta\hat{k}, \tau) \;=\; \frac{\mathcal{N}^-}{\mathcal{N}} H^-(\Delta\hat{k}, \tau) \;+\; \frac{\mathcal{N}^+}{\mathcal{N}} H^+(\Delta\hat{k}, \tau). \tag{27}$$

This relationship is useful to compute moments of adjusters. For example, the average duration of inaction equals the weighted sum of the average conditional durations:

$$\overline{\mathbb{E}}[\tau] \;=\; \overline{\mathbb{E}}\left[\mathbb{E}[\tau|\Delta k]\right] \;=\; \frac{\mathcal{N}^-}{\mathcal{N}}\overline{\mathbb{E}}^-[\tau] \;+\; \frac{\mathcal{N}^+}{\mathcal{N}}\overline{\mathbb{E}}^+[\tau]. \tag{28}$$

However, we need to leverage another approach to recover the unconditional distribution of firms. In that case, the shares must be rescaled by the relative durations of inaction:

$$g(\hat{k}) \;=\; \frac{\mathcal{N}^-}{\mathcal{N}}\frac{\overline{\mathbb{E}}^-[\tau]}{\overline{\mathbb{E}}[\tau]}\, g^-(\hat{k}) \;+\; \frac{\mathcal{N}^+}{\mathcal{N}}\frac{\overline{\mathbb{E}}^+[\tau]}{\overline{\mathbb{E}}[\tau]}\, g^+(\hat{k}) \;=\; \mathcal{N}^-\,\overline{\mathbb{E}}^-[\tau]\, g^-(\hat{k}) \;+\; \mathcal{N}^+\,\overline{\mathbb{E}}^+[\tau]\, g^+(\hat{k}), \tag{29}$$

where we simplify the expression using $\overline{\mathbb{E}}[\tau] = \mathcal{N}^{-1}$, that is, the average duration of inaction equals the inverse of the total frequency of adjusters. This implies that the duration-adjusted frequencies also sum up to one, i.e., $\mathcal{N}^-\,\overline{\mathbb{E}}^-[\tau] + \mathcal{N}^+\,\overline{\mathbb{E}}^+[\tau] = 1$. Why do we need to rescale by duration? The answer is the *fundamental renewal property:* The average behavior in the economy is attributable to firms with longer periods of inaction (which are observed less frequently). Adjusting the shares with their relative duration corrects this observational bias. In environments with partial irreversibility, the slowly-adjusting firms are coincidentally those that make downward adjustments.

**Illustrative example.** Consider an economy in which most firms make frequent upward adjustments. The durations of inaction are $\overline{\mathbb{E}}[\tau] = 2$, $\overline{\mathbb{E}}^-[\tau] = 1.5$, and $\overline{\mathbb{E}}^+[\tau] = 4$, and the frequencies are $\mathcal{N} = 0.5$, $\mathcal{N}^- = 0.4$, and $\mathcal{N}^+ = 0.1$.[11] The shares of upward and downward adjustments are $\mathcal{N}^-/\mathcal{N} = 0.8$ and $\mathcal{N}^+/\mathcal{N} = 0.2$, and the relative durations are $\overline{\mathbb{E}}^-[\tau]/\overline{\mathbb{E}}[\tau] = 0.75$ and $\overline{\mathbb{E}}^+[\tau]/\overline{\mathbb{E}}[\tau] = 2$. While only 20% of adjustments are downward, they happen after longer inactions spells with twice the average duration, implying that the underlying states $\hat{k}$ generating those adjustments are occupied for longer periods of time. To account for this higher occupancy, the implied duration-modified frequencies, $\mathcal{N}^-\,\overline{\mathbb{E}}^-[\tau] = 0.6$ and $\mathcal{N}^+\,\overline{\mathbb{E}}^+[\tau] = 0.4$, are the appropriate weights to recover the unconditional distribution of firms as $g = 0.6\,g^- + 0.4\,g^+$.

**Remarks on the fixed costs.** Following Cooper and Haltiwanger (2006), fixed capital adjustment costs $\theta_s$ reflect disruptions arising from the installation (or disinstallation) of capital, costly learning, time-to-build, search frictions, among other factors. We specify fixed costs to be deterministic, symmetric (the same costs are paid indistinctly for positive and negative investments), and equal across firms. We abstracted from other frictions and heterogeneity to keep the presentation simple. However, we prove all the results for the generalized hazard model proposed by Caballero and Engel (1999, 2007) and examined in contemporaneous work by Álvarez, Lippi and

[11] Note that $\overline{\mathbb{E}}[\tau] = 1/\mathcal{N}$ but $\overline{\mathbb{E}}^{\pm}[\tau] \neq 1/\mathcal{N}^{\pm}$.

Oskolkov (2020). This generalized hazard model accommodates asymmetric fixed costs, random fixed costs, as well as time-dependent adjustments motivated with information frictions (Verona, 2014) or search frictions (Kurmann and Petrosky-Nadeau, 2007; Ottonello, 2018). Appendix B presents and discusses the generalized hazard model. Also see Baley and Blanco (2021) for ex-ante heterogeneity in fixed adjustment costs across sectors.

# 3 Three macroeconomic outcomes

How do investment frictions shape aggregate capital's allocation, valuation, and fluctuations? This section defines these macroeconomic outcomes and provides characterizations using moments of the cross-sectional distribution $g(\hat{k})$ and observable statistics.

## 3.1 Capital allocation

Following the development literature, we define *capital misallocation* as the cross-sectional variance of the log marginal revenue product of capital. In our model all firms produce the same good and the output price is normalized to one. Thus, we measure the variance of marginal products instead. From the production function (1), the log of the marginal product of capital is collinear to a firm's capital-productivity ratio $\hat{k}$, that is, $\log mpk_s = \log \alpha - (1-\alpha)\hat{k}_s$. Therefore, misallocation is proportional to $\mathbb{V}ar[\hat{k}]$:

$$\mathbb{V}ar[\log mpk] \;=\; (1-\alpha)^2 \mathbb{V}ar[\hat{k}]. \tag{30}$$

In a frictionless environment, $\hat{k}_s$ is constant and $\mathbb{V}ar[\log mpk] = 0$. With frictions, however, dispersion in the marginal product of capital arises, as in Asker, Collard-Wexler and De Loecker (2014). Given the collinear relationship established in (30), we will use the term misallocation when referring to $\mathbb{V}ar[\hat{k}]$.

**Measuring misallocation with microdata.** The challenge in measuring misallocation is that the distribution $g(\hat{k})$ is not observed. As economists, however, we have access to detailed panel data $\Omega = \{\Delta\hat{k}, \tau\}$ with information on the actions of adjusters: the size of discrete adjustments $\Delta\hat{k}$ in (8) and the duration of completed inaction spells $\tau$ in (12). We present mappings that use micro investment data $\Omega$ to recover the level of capital misallocation in the economy. We proceed in two steps. Proposition 1 recovers the parameters of the stochastic process and the two reset points through a system of equations incorporating several moments from the distribution of adjusters.[12] Then, given the reset points, Proposition 2 recovers the population mean $\mathbb{E}[\hat{k}]$ and variance $\mathbb{V}ar[\hat{k}]$ of capital-productivity ratios.

[12] Appendix E.4 develops an iterative method to solve the non-linear system in equations (31) to (34).

**Proposition 1.** *Let* $\Phi(\nu,\sigma^2) \equiv \log\left(\alpha A/(r+\alpha\nu-\alpha^2\sigma^2/2)\right)$. *The parameters of the stochastic process for productivity* $(\nu,\sigma^2)$ *and the reset points* $(\hat{k}^{*-},\hat{k}^{*+})$ *are recovered from the microdata* $\Omega \equiv (\Delta\hat{k},\tau)$ *through the following system:*

$$\nu = \frac{\overline{\mathbb{E}}[\Delta\hat{k}]}{\overline{\mathbb{E}}[\tau]}, \tag{31}$$

$$\sigma^2 = \frac{\overline{\mathbb{E}}[(\hat{k}_\tau+\nu\tau)^2]-\overline{\mathbb{E}}[(\hat{k}^*)^2]}{\overline{\mathbb{E}}[\tau]}, \tag{32}$$

$$\hat{k}^{*-} = \frac{1}{1-\alpha}\left[\Phi(\nu,\sigma^2) - \log(p^{buy}) + \log\left(\frac{1-\overline{\mathbb{E}}^-\left[e^{-\hat{r}\tau+\alpha\left(\hat{k}_\tau-\hat{k}^{*+}\right)}\right]}{1-\overline{\mathbb{E}}^-\left[\frac{p(\Delta\hat{k})}{p^{buy}}e^{-\hat{r}\tau+\hat{k}_\tau-\hat{k}^{*+}}\right]}\right)\right], \tag{33}$$

$$\hat{k}^{*+} = \frac{1}{1-\alpha}\left[\Phi(\nu,\sigma^2) - \log(p^{sell}) + \log\left(\frac{1-\overline{\mathbb{E}}^+\left[e^{-\hat{r}\tau+\alpha\left(\hat{k}_\tau-\hat{k}^{*-}\right)}\right]}{1-\overline{\mathbb{E}}^+\left[\frac{p(\Delta\hat{k})}{p^{sell}}e^{-\hat{r}\tau+\hat{k}_\tau-\hat{k}^{*-}}\right]}\right)\right]. \tag{34}$$

Expression (31) recovers the drift from the average adjustment size times the frequency of adjustment (the inverse of the expected duration of inaction $\mathcal{N} = \overline{\mathbb{E}}[\tau]^{-1}$), while expression (32) recovers the volatility from the variance in adjustment size.[13] Expressions (33) and (34) recover the reset points. The first term $\Phi(\nu,\sigma^2)$ reflects the ratio of marginal product to the user cost of capital. Through this ratio, both reset states increase with profitability $A$ and idiosyncratic risk $\sigma^2$ and decrease with the discount $r$ and the drift $\nu$. The second term shows that reset points decrease with the corresponding investment price: firms invest more the lower is the purchasing price $p^{buy}$ and disinvest less the lower is the selling price $p^{sell}$. Lastly, the third term shows how investment frictions shape the reset points through the marginal profits accrued during periods of inaction (in the numerator) and the resale value (in the denominator). As long as $(\tau,\Delta\hat{k})$ depend on the last reset point, endogenous irreversibility arises beyond the exogenous price wedge.

With the reset points and parameters in hand, we proceed to recover the unconditional mean $\mathbb{E}[\hat{k}]$ and variance $\mathbb{V}ar[\hat{k}]$ of capital-productivity ratios $\hat{k}$.

**Proposition 2.** *Let* $\Omega \equiv (\Delta\hat{k},\tau)$ *be a panel of observations. For each inaction spell find the departing point* $\hat{k}^*$ *and the ending point* $\hat{k}_\tau$ *using* (14) *and* (15). *Then the unconditional mean and variance of* $\hat{k}$ *are recovered from the microdata as follows:*

[13] We obtained similar mappings from the data to the parameters in Baley and Blanco (2021) for the case without irreversibility. Irreversibility does not change the mapping to the drift, but it changes the mapping to the volatility.

$$\text{(35)} \qquad \mathbb{E}[\hat{k}] = \overline{\mathbb{E}}\left[\overline{\mathbb{E}}\left[\left(\frac{\hat{k}^* + \hat{k}_\tau}{2}\right)\left(\frac{\hat{k}^* - \hat{k}_\tau}{\overline{\mathbb{E}}[\Delta\hat{k}]}\right)\middle|\Delta\hat{k}\right]\right] + \frac{\sigma^2}{2\nu},$$

$$\text{(36)} \qquad \mathbb{V}ar[\hat{k}] = \overline{\mathbb{E}}\left[\overline{\mathbb{E}}\left[\left((\hat{k}^* - \mathbb{E}[\hat{k}])(\hat{k}_\tau - \mathbb{E}[\hat{k}]) + \frac{(\hat{k}^* - \hat{k}_\tau)^2}{3}\right)\left(\frac{\hat{k}^* - \hat{k}_\tau}{\overline{\mathbb{E}}[\Delta\hat{k}]}\right)\middle|\Delta\hat{k}\right]\right].$$

The mapping in (35) recovers the population mean $\mathbb{E}[\hat{k}]$ from the average midpoint between the departing and the ending points of an inaction spell $(\hat{k}^* + \hat{k}_\tau)/2$, where the average is computed under a change of measure induced by the renewal weights $(\hat{k}^* - \hat{k}_\tau)/\overline{\mathbb{E}}[\Delta\hat{k}]$. To recover the population mean, the renewal measure overweighs the midpoints of adjusters with longer periods of inaction, which are more representative in the population.[14] The term $\sigma^2/2\nu$ corrects for the accumulated drift between adjustments. Similarly, the mapping in (36) recovers the population variance $\mathbb{V}ar[\hat{k}]$ from the average distance between the departing point and the mean $(\hat{k}^* - \mathbb{E}[\hat{k}])$, the ending point and the mean $(\hat{k}_\tau - \mathbb{E}[\hat{k}])$, and the between departing and ending points $(\hat{k}^* - \hat{k}_\tau)^2$, again computed using the renewal distribution. In these expressions, we compute the inner expectation with $H^-$ or $H^+$ depending on the sign of the last adjustment and compute the outer expectation with shares of upward $\mathcal{N}^-/\mathcal{N}$ and downward $\mathcal{N}^+/\mathcal{N}$ adjustment in the population.

**Economic forces shaping capital misallocation.** Using the law of total variance, we decompose misallocation $\mathbb{V}ar[\hat{k}]$ into two terms that condition on the last adjustment:

$$\text{(37)} \qquad \underbrace{\mathbb{V}ar[\hat{k}]}_{\text{total}} = \underbrace{\mathbb{E}\left[\mathbb{V}ar[\hat{k}|\Delta\hat{k}]\right]}_{\text{within}} + \underbrace{\mathbb{V}ar\left[\mathbb{E}[\hat{k}|\Delta\hat{k}]\right]}_{\text{between}}.$$

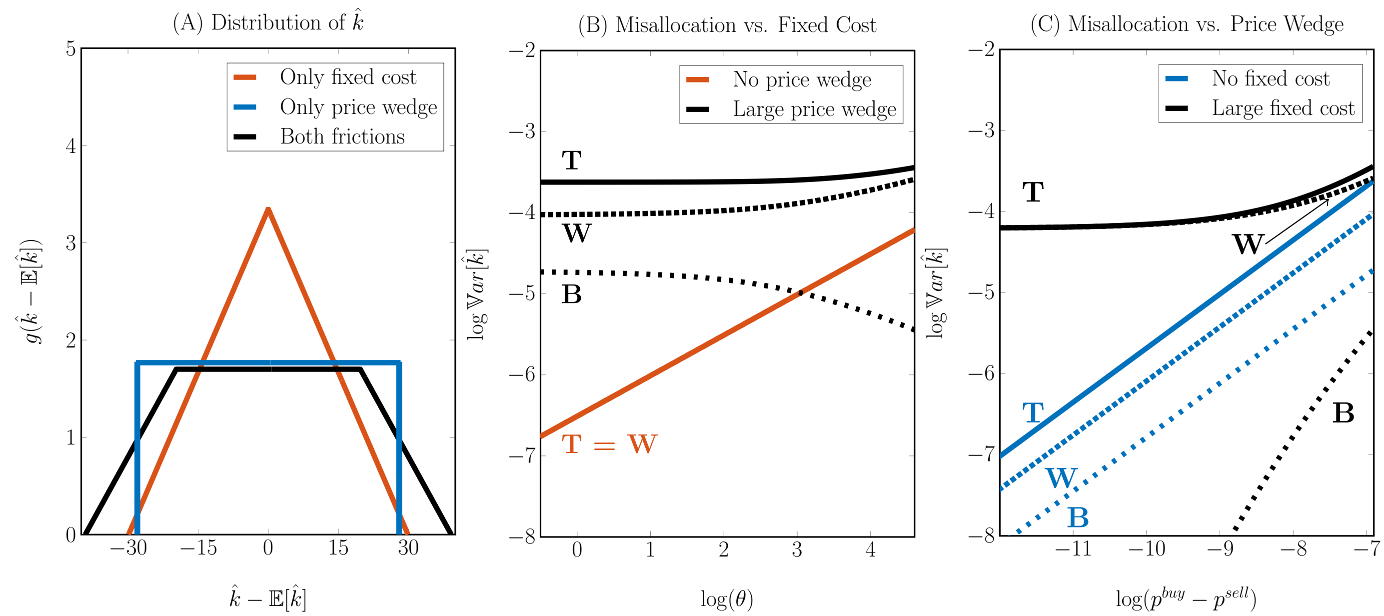
The decomposition in (37) is useful to assess the relative importance of each investment friction in generating capital misallocation. Later in the paper, we come back to this decomposition to examine the interaction of corporate taxation and investment frictions in generating misallocation.

The first term is the average of the variance *within* each conditional distribution $g^+$ and $g^-$, that is, the average of $\mathbb{V}ar^-[\hat{k}]$ and $\mathbb{V}ar^+[\hat{k}]$ (computed from (36) conditioning on the sign of $\Delta\hat{k}$ and using the conditional renewal measure as in (28)). Both investment frictions add to this dispersion. The second term reflects the distance *between* the conditional means $\mathbb{E}^-[\hat{k}]$ and $\mathbb{E}^+[\hat{k}]$ (computed from (35) conditioning on the sign of $\Delta\hat{k}$ and using the conditional renewal measure). This term arises exclusively from the price wedge that generates two different means. The larger the price wedge, the further apart are the conditional means and the larger the between variance. Note that this term is zero when only fixed costs are present as there is a unique reset point.

Next, we show that the relative size of frictions affects the response of misallocation to an

[14] Without the price wedge, the renewal weights are equal to the relative size of adjustment $\Delta k/\overline{\mathbb{E}}[\Delta\hat{k}]$.

**Figure III** – Misallocation and Investment Frictions




Notes: Panel A plots the steady-state distribution of capital-productivity ratios, normalized by their mean. Triangle = only fixed costs; Rectangle = only price wedge; Parallelogram = both frictions. Panel B plots misallocation against the fixed cost for a zero (orange) and a large (black) price wedge. Panel C plots misallocation against the price wedge for a zero (blue) and a large (black) fixed cost. Variances: total (T), within (W) and between (B).

increase in these frictions. Figure III illustrates the effects of each adjustment friction on the total, within, and between variances of capital-productivity ratios. To sharpen the exposition, we assume zero drift ($\nu = 0$) and a symmetric price wedge ($p^{buy} - p = p - p^{sell}$). Panel A plots the stationary density $g(\hat{k})$. Panels B and C are log-log plots of misallocation against one friction, setting the other friction either at zero or at a large value. We use a log-log scale to facilitate the visual analysis and to highlight the linearity that arises in certain relationships. We also mark within (W), between (B), and total (T) variances.

Consider an environment where the fixed cost is the only investment friction (orange lines). The density is a triangle that concentrates at the unique reset point and decreases linearly toward the boundaries of the inaction region. A higher fixed cost widens the inaction region and increases misallocation in a log-log linear way (Panel B). Now consider an environment where the price wedge is the only investment friction (blue lines). The density is a rectangle between the two reset/inaction points. In this case, a higher price wedge increases all components of misallocation (within and between) in a log-log linear way (Panel C).

With both frictions active (black lines), the density is a trapezoid. The relationship between misallocation and frictions is now flattened in the following sense. Consider the case with fixed costs and a large price wedge. Misallocation is at a higher level but the relationship between misallocation and the fixed cost flattens out. A higher fixed cost still widens the distance between inaction thresholds, increasing the within variance, but simultaneously reduces the distance between the reset points, decreasing the between variance. These opposing forces compensate each other cancelling the effects on misallocation (see the dotted and dashed black lines in Panel B which move in opposite directions). Now consider the case with partial irreversibility and a large fixed cost. Again, misallocation is at a higher level and the relationship between misallocation and the price wedge flattens out. The between variance disappears (its log becomes very negative).

## 3.2 Capital valuation

Following the finance literature, we define capital valuation as the weighted average of individual $q(\hat{k})$ in (21) with weights $\omega(\hat{k}) \equiv e^{\hat{k}}/\hat{K}$, divided by the average investment price $p \equiv \overline{\mathbb{E}}[p(\Delta\hat{k})]$:

$$q \;\equiv\; \frac{1}{p}\int_{\hat{k}^-}^{\hat{k}^+} q(\hat{k})\omega(\hat{k})g(\hat{k})\,\mathrm{d}\hat{k} \;=\; \frac{\mathbb{E}[v'(\hat{k})]}{p\hat{K}}. \tag{38}$$

In contrast to the individual $q(\hat{k})$, the definition of the aggregate $q$ divides by the investment price. Aggregate $q$ is a measure of the average propensity to invest. Without frictions, there is a unique investment price, and optimality implies that $q = 1$ always. That is, all investment or disinvestment opportunities are immediately implemented, eliminating any possibility for $q$ to deviate from 1. With frictions, $q$ may differ from one. If $q > 1$, the average marginal valuation of capital is larger inside the firms than outside them, and the average propensity to invest is positive.

**Characterization of aggregate $q$.** We proceed to characterize the aggregate $q$ in terms of moments of $\hat{k}$. But first, we consider the average capital gains or loses $\mathcal{P}(\hat{k})$ accrued to a firm that trades capital at the state $\hat{k}$ (that is, assuming fixed costs are zero). To the left of the inner inaction region, the firm would buy capital making an average capital loss of $p^{buy}/p - 1$ per unit bought. To the right of the inner action region, the firm would sell capital making an average capital gain of $p^{sell}/p - 1$ per unit sold. Within the inner inaction region, even in the absence of fixed costs, firms would never adjust their capital stock. However, we extend capital gains within the inner action region $[\hat{k}^{*+}, \hat{k}^{*-}]$ to facilitate the computation of expected capital gains. Inside the inner inaction region, $\mathcal{P}(\hat{k})$ sets a price determined by a differentiability requirement.[15]

Formally, we let $\mathcal{P}(\hat{k}) \in \mathbb{C}^2$ be a twice continuously differentiable function in the domain $[\hat{k}^+, \hat{k}^-]$ such that:

$$\mathcal{P}(\hat{k}) \;\equiv\; \begin{cases} p^{\text{buy}}/p - 1 & \text{if } \hat{k} \in [\hat{k}^-, \hat{k}^{*-}], \\ p^{\text{sell}}/p - 1 & \text{if } \hat{k} \in [\hat{k}^{*+}, \hat{k}^+]. \end{cases} \tag{39}$$

Since $\mathcal{P}(\hat{k})$ equals the deviations from the average price, it averages zero: $\overline{\mathbb{E}}[\mathcal{P}(\hat{k}^*)] = 0$.

[15] The exact definition of $\mathcal{P}(\hat{k})$ in the inner inaction region does not matter as firms never adjust in that region.

With the definition of the auxiliary price-deviation function, Proposition 3 expresses the aggregate $q$ in terms of cross-sectional moments and parameters. The proof combines the HJB equation for $v'(\hat{k})$ in (16), which specifies firms' optimal behavior, with the KFE for $g(\hat{k})$ in (22), which describes the evolution of firms through the cross-sectional distribution, into a single "master equation." Then we integrate the master equation to eliminate idiosyncratic noise and recover aggregate variables.

**Proposition 3.** *Aggregate $q$ equals:*

$$q = \frac{1}{r}\left(\underbrace{\frac{\alpha A\hat{Y}}{p\hat{K}} + \left(\frac{\sigma^2}{2} - \nu\right)}_{productivity} + \underbrace{\mathbb{E}\left[\frac{1}{\mathrm{d}s}\mathbb{E}_s\left[\mathrm{d}(\mathcal{P}(\hat{k}_s)\omega(\hat{k}_s))\right]\right]}_{irreversibility}\right), \tag{40}$$

*where aggregate productivity $\hat{Y}/\hat{K}$ is equal, up to second order, to*

$$\frac{\hat{Y}}{\hat{K}} = \frac{\mathbb{E}[e^{\alpha\hat{k}}]}{\mathbb{E}[e^{\hat{k}}]} = \exp\left\{-(1-\alpha)\left(\mathbb{E}[\hat{k}] + \frac{\alpha}{2}\mathbb{V}ar[\hat{k}]\right)\right\} + o(\hat{k}^3), \tag{41}$$

*and the irreversibility term is negative, and up to first order, it is equal to*

$$\mathbb{E}\left[\frac{1}{\mathrm{d}s}\mathbb{E}_s\left[\mathrm{d}(\mathcal{P}(\hat{k}_s)\omega(\hat{k}_s))\right]\right] \approx -\frac{\overline{\mathbb{C}ov}\left[\Delta\hat{k}, \mathcal{P}(\hat{k}^*)\right]}{\overline{\mathbb{E}}[\tau]} < 0. \tag{42}$$

**Economic forces shaping capital valuation.** Aggregate $q$ in (40) equals the perpetuity value of three terms. The first term is aggregate productivity $\hat{Y}/\hat{K}$ equal to the average output-productivity ratio divided by the average capital-productivity ratio.[16] Observe that $q$ increases with aggregate productivity; in turn, because of decreasing returns to scale $\alpha < 1$, aggregate productivity decreases with the average $\mathbb{E}[\hat{k}]$ and the dispersion $\mathbb{V}ar[\hat{k}]$ of capital-productivity ratios (see equation (41)). Consequently, aggregate $q$ also decreases with the level and the dispersion of $\hat{k}$. Both the fixed cost and the price wedge affect $q$ indirectly through this channel.

The second term reflects the expected change in the average capital-productivity ratio, which takes into account the deterministic trend $\nu$ and the risk $\sigma^2$. Since firms can upsize to exploit good outcomes and can downsize to insure against bad outcomes, they are effectively risk loving (Oi, 1961; Hartman, 1972; Abel, 1983). Thus, an increase in idiosyncratic risk $\sigma^2$ directly increases $q$. At the same time, an increase in idiosyncratic risk indirectly affects $q$ by increasing misallocation and thus lowering the aggregate output-capital ratio in (41). The overall effect of risk on $q$ depends on the relative strength of these two opposing forces.

In addition to irreversibility's indirect effect on $q$ through misallocation, it also has a direct negative effect on $q$, as in Sargent (1980). The irreversibility term equals the expected price

[16] Aggregate productivity differs from the average output-capital ratio $\mathbb{E}[y/k] = \mathbb{E}[e^{(\alpha-1)\hat{k}}]$ due to heterogeneity.

deviations from the average price weighted by the capital stock. Expression (42) maps it to minus the covariance of investment $\Delta\hat{k}$ and price deviations $\mathcal{P}(\Delta\hat{k})$. This covariance is positive since firms purchase capital at a price above the average and sell capital at a price below the average. Since the covariance is positive, irreversibility reduces $q$. Intuitively, firms seek to avoid histories in which, after upsizing, negative productivity shocks will force them to downsize and face the penalty of selling their capital at a discount. Firms also seek to avoid histories in which, after downsizing, positive productivity shocks will force them to upsize and face the penalty of purchasing back capital at a higher price. To minimize the likelihood of these "switching" situations, firms under-invest and under-disinvest, effectively reducing capital valuation.

**Individual vs. aggregate $q$.** In Section 2.4 we showed that individual $q(\hat{k})$ is a non-monotonic function of $\hat{k}$. This observation has led some economists to argue that the individual non-monotonicity translates into aggregate non-monotonicity, discarding $q$ as a sufficient statistic for aggregate investment.[17] Expression (40) shows that this argument is flawed. Fixed adjustment costs and partial irreversibility do not break the decreasing relation between aggregate $q$ and aggregate $\hat{K}$. While this result is counterintuitive, it is a natural consequence of aggregating the behavior of individual firms. The anticipatory effects that bend individual $q(\hat{k})$ in the vicinity of the borders of the inaction region disappear when aggregating the cross-section, as positive and negative stances of expected changes in $q(\hat{k})$ cancel each other out in the aggregate. As a result, aggregate $q$ *is a sufficient statistic for aggregate investment.*

### 3.3 Capital fluctuations

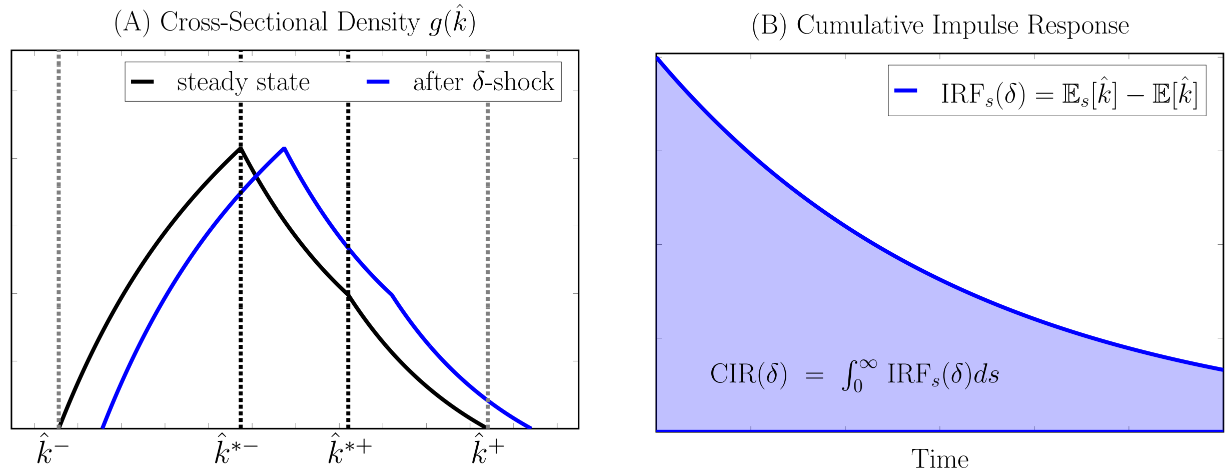
Following the business cycle literature, we define capital fluctuations as *the transitional dynamics of aggregate capital following an aggregate productivity shock*. Starting from the steady state, we introduce a small, permanent, and unanticipated decrease in the (log) level of productivity of size $\delta > 0$ to all firms (see Alexandrov (2021) for the characterization of transitional dynamics following large aggregate shocks). We normalize the arrival date of the aggregate shock to $s = 0$, so all firms' productivity and capital-productivity ratios change to

$$(43) \qquad \log(u_0) = \log(u_{0^-}) - \delta; \qquad \log(\hat{k}_0) = \log(\hat{k}_{0^-}) + \delta.$$

Panel A of Figure IV plots the initial density following the $\delta$ productivity shock (black line) next to the steady-state density $g(\hat{k})$ (blue line). The new distribution displaces horizontally to the right relative to the steady-state distribution. Our exercise consists in tracking the mean $\mathbb{E}_s[\hat{k}]$ as it makes its way back to its steady-state value $\mathbb{E}[\hat{k}]$. By assuming a constant interest rate, investment

[17] See Tobin (1969); Abel (1979); Hayashi (1982); Abel and Eberly (1996) and Caballero and Leahy (1996) for alternative views on the role of $q$ as a sufficient statistic for aggregate investment.

**Figure IV** – Distribution Dynamics and Cumulative Impulse Response




Notes: Panel A shows the steady-state distribution $g(\hat{k})$ (blue line) and the initial distribution following a productivity shock (blue line). Panel B shows the $\text{IRF}(\delta, s)$ (solid blue line) and the CIR (area).

policies do not respond to changes in the distribution and remain fixed along the transition path. Therefore, our analysis measures the strength of the partial equilibrium response to aggregate shocks.[18]

We define the impulse-response function, denoted by $\text{IRF}(\delta, s)$, measured $s$ periods after an aggregate productivity shock of size $\delta$ as follows:

$$\text{IRF}(\delta, s) \equiv \mathbb{E}_s[\hat{k}] - \mathbb{E}[\hat{k}], \tag{44}$$

where $\mathbb{E}_s[\cdot]$ denotes expectations with the time-$s$ distribution.

We define the cumulative impulse response $\text{CIR}(\delta)$, as the area under the $\text{IRF}_s(\delta)$ function across all dates $s \in (0, \infty)$

$$\text{CIR}(\delta) \equiv \int_0^\infty \text{IRF}_s(\delta) \; \mathrm{d}s. \tag{45}$$

Panel B in Figure IV plots these two objects. The solid line is the impulse-response function $\text{IRF}(\delta, s)$, and the area underneath it is the cumulative impulse response function $\text{CIR}(\delta)$. The CIR is a useful metric. It summarizes both the impact and persistence of the response, eases the comparison across different models, and represents a "multiplier" of aggregate shocks. It is illustrative to compare the CIR with and without adjustment frictions. Without frictions, firms respond instantly to the aggregate shock and the CIR is zero. With frictions, the larger the CIR

[18]While assuming a constant interest rate (and investment policies) along the transition is an extreme assumption, Winberry (2021) shows that the interest rate response to aggregate productivity shocks is small and even countercyclical. Appendix C relaxes this assumption and presents a general equilibrium model that delivers constant prices as an equilibrium outcome.

the longer it takes firms to respond to the aggregate shock and the slower the transitional dynamics.

**Characterization of the CIR.** Next, we expresses the CIR as a function of cross-sectional moments of $\hat{k}$. We use a strategy analogous to the one we employed above to characterize aggregate $q$, where by we define an auxiliary function that allow us to characterize the role of irreversibility. As a first step, we define two values $\mathcal{M}^{buy} < 0 < \mathcal{M}^{sell}$ that measure the expected cumulative deviation of the capital-productivity ratio relative to the mean $\mathbb{E}[\hat{k}]$ conditional on the last adjustment:

$$\mathcal{M}^{buy} \equiv (\mathbb{E}^{-}[\hat{k}] - \mathbb{E}[\hat{k}])\overline{\mathbb{E}}^{-}[\tau]\ \frac{\mathbb{E}[\mathbb{P}^{+}]}{\mathbb{P}^{-+}} < 0, \tag{46}$$

$$\mathcal{M}^{sell} \equiv (\mathbb{E}^{+}[\hat{k}] - \mathbb{E}[\hat{k}])\overline{\mathbb{E}}^{+}[\tau]\ \frac{\mathbb{E}[\mathbb{P}^{-}]}{\mathbb{P}^{+-}} > 0. \tag{47}$$

Before we proceed further, let us explain how $\mathcal{M}^{buy}$ in (46) captures upsizing firms' behavior (analogously, $\mathcal{M}^{sell}$ in (47) captures firms' downsizing behavior). Upsizing firms reset their capital-productivity ratio below the unconditional mean and, on average, remain below the mean for the duration of their inaction spell. The average deviation accumulated during one inaction spell is then $(\overline{\mathbb{E}}^{-}[\hat{k}] - \mathbb{E}[\hat{k}])\overline{\mathbb{E}}^{-}[\tau]$. Since investment sign is serially correlated, upsizing firms remain in an upsizing phase contributing to negative deviations for several periods; they would only leave this phase after a series of negative shocks makes them downsize. The ratio $\mathbb{E}[\mathbb{P}^{+}]/\mathbb{P}^{-+}$ exactly reflects the average time spent in the transient upsizing phase, where $\mathbb{E}[\mathbb{P}^{+}] \equiv \Pr[\Delta\hat{k}' < 0]$ is the unconditional probability of downsizing and $\mathbb{P}^{-+} \equiv \Pr[\Delta\hat{k}' < 0|\Delta\hat{k} > 0]$ is the probability of downsizing conditional on being currently in an upsizing phase.[19]

As a second step, we define an auxiliary function $\mathcal{M}(\hat{k}) \in \mathbb{C}^2$ that characterizes the cumulative deviations within the inner inaction region. This function is identical to $\mathcal{P}(\hat{k})$ in (39), but replacing the price deviations with the quantities $\mathcal{M}^{buy}$ and $\mathcal{M}^{sell}$:

$$\mathcal{M}(\hat{k}) = \begin{cases} \mathcal{M}^{buy} & \text{if } \hat{k} \in [\hat{k}^{-}, \hat{k}^{*-}] \\ \mathcal{M}^{sell} & \text{if } \hat{k} \in [\hat{k}^{*+}, \hat{k}^{+}]. \end{cases} \tag{48}$$

Note that $\overline{\mathbb{E}}[\mathcal{M}(\hat{k}^{*})] = 0$ because $\mathcal{M}(\hat{k})$ equals the cumulative capital deviations from the steady-state. Using the auxiliary capital-deviation function $\mathcal{M}(\hat{k})$, Proposition 4 characterizes the CIR.

**Proposition 4.** *The CIR of the average log capital-productivity ratio* $\mathbb{E}[\hat{k}]$ *following a marginal*

[19]The unconditional probability of downsizing is measured in the data as $\mathbb{E}[\mathbb{P}^{+}] = \overline{\mathbb{E}}[\tau\mathbb{I}(\Delta\hat{k} < 0)]/\overline{\mathbb{E}}[\tau]$.

*aggregate productivity shock of size $\delta > 0$ is equal, up to first order, to*

$$\frac{CIR(\delta)}{\delta} = \underbrace{\frac{\mathbb{V}ar[\hat{k}]}{\sigma^2}}_{variance} + \underbrace{\frac{\nu \mathbb{C}ov[\hat{k}, a]}{\sigma^2}}_{covariance} + \underbrace{\mathbb{E}\left[\frac{1}{\mathrm{d}s}\mathbb{E}_s[\mathrm{d}(\mathcal{M}(\hat{k}_s)\hat{k}_s)]\right]}_{irreversibility} + o(\delta), \tag{49}$$

*where the variance is recovered from the microdata in (36), the covariance is recovered as*

$$\mathbb{C}ov[\hat{k}, a] = \frac{1}{2\nu}\left(\mathbb{V}ar[\hat{k}] - \frac{\overline{\mathbb{E}}[(\hat{k}_\tau - \mathbb{E}[\hat{k}])^2\tau]}{\overline{\mathbb{E}}[\tau]} + \frac{\sigma^2}{2}\frac{\overline{\mathbb{E}}[\tau]}{2}(1 + \overline{\mathbb{CV}}^2[\tau])\right), \tag{50}$$

*and the irreversibility term is equal to*

$$\mathbb{E}\left[\frac{1}{\mathrm{d}s}\mathbb{E}_s\left[\mathrm{d}(\mathcal{M}(\hat{k}_s)\hat{k}_s)\right]\right] = -\frac{\overline{\mathbb{C}ov}[\Delta\hat{k}, \mathcal{M}(\Delta\hat{k})]}{\overline{\mathbb{E}}[\tau]} > 0. \tag{51}$$

**Economic forces shaping capital fluctuations.** According to (49), the CIR equals a linear combination of two steady-state moments and an irreversibility term. The moments are the cross-sectional variance of capital-productivity ratios $\mathbb{V}ar[\hat{k}]$ and the covariance of capital-productivity ratios $\hat{k}$ with the time elapsed since the last adjustment $\mathbb{C}ov[\hat{k}, a]$. These steady-state moments are informative about transitional dynamics because aggregate shocks $\delta$ and idiosyncratic shocks $u$ enter symmetrically into $\hat{k}$, and as a consequence, how firms respond to idiosyncratic shocks inform how they respond to aggregate shocks. Specifically, the variance $\mathbb{V}ar[\hat{k}]$ reflects insensitivity to idiosyncratic shocks, while the covariance $\mathbb{C}ov[\hat{k}, a]$ reflects asymmetric costs of downsizing vs. upsizing.[20] Our work in Baley and Blanco (2021) established the relationship between the CIR and these two steady-state moments in environments with drift, asymmetric fixed costs, and random opportunities of free adjustment, but without partial irreversibility. In those environments, the irreversibility term equals zero.

Let us now discuss the role of irreversibility for the CIR, which slows down the propagation of aggregate shocks according to positive sign of (51). The irreversibility term measures the change in cumulative deviations $\mathcal{M}^{sell}$ and $\mathcal{M}^{buy}$ due to the aggregate shock. Concretely, the aggregate shock $\delta$ increases the probability of downward adjustments as firms need to downsize to reflect the reduction in aggregate productivity. Due to the serial correlation of investment sign, a downsizing phase commences. Recall that, after downsizing, firms remain above the steady-state average capital-productivity ratio. Thus, after an aggregate shock, firms are more likely to remain above the average than before the shock, slowing down the convergence of the average $\mathbb{E}_s[\hat{k}]$ to its long-run value $\mathbb{E}[\hat{k}]$.

Besides its direct effect, irreversibility has an indirect effect on the CIR which increases the

[20] Fang (2021) uses the covariance $\mathbb{C}ov[\hat{k}, a]$ to calibrate a model with asymmetric fixed costs and assess the role of firm-level uncertainty for the effectiveness of monetary policy.

cross-sectional moments $\mathbb{V}ar[\hat{k}]$ and $\mathbb{C}ov[\hat{k}, a]$. In the data, this indirect effect dominates. Identifying and characterizing the irreversibility term in the CIR is one of the key contributions of our analysis, as it opens to door to study transitional dynamics in environments with history dependence, that is, where the first stopping time does not fully absorb the effects of an aggregate shock. This type of problems are labeled as problems with reinjection by Álvarez and Lippi (2021).

**CIR of functions of $\hat{k}$.** Our characterization of average capital fluctuations in (49) can be generalized to consider the transitional dynamics of any continuous function $f(\hat{k})$ following an aggregate shock $\delta$. In the generalized formula the values $\mathcal{M}^{buy}$ and $\mathcal{M}^{sell}$ behind the function $\mathcal{M}(\hat{k})$ are appropriately redefined to track the deviations of the time-$s$ average value of $f$, $\mathbb{E}_s[f(\hat{k})]$, from its steady-state value $\mathbb{E}[f(\hat{k})]$. This generalization could in principle be useful to study fluctuations in capital misallocation as in Bachmann and Bayer (2014), Ehouarne, Kuehn and Schreindorfer (2016), and Lanteri (2018), by setting the function to $f(\hat{k}) = (\hat{k} - \mathbb{E}[\hat{k}])^2$, or dynamics of aggregate marginal valuation (the numerator of aggregate $q$) by setting $f(\hat{k}) = v'(\hat{k})$.

# 4 The Macroeconomic Effects of Corporate Taxes

This section introduces a comprehensive tax schedule into the firm problem and analytically characterizes the role of corporate taxation in shaping macroeconomic outcomes. We do this in three steps. First, we show that taxes change four parameters: profitability $A$, the discount factor $\rho$, the fixed cost $\theta$, and the investment prices $p(\Delta\hat{k})$. Once we redefine these parameters, the investment problem is identical to the one described in Section 2. Second, we decompose the firm investment policy into a neoclassical component, which reflects the effects of taxation through the user cost of capital, and a dynamic component, which reflects the interaction of taxes and investment frictions. Third, we isolate the various mechanisms at play by considering two benchmark cases: a driftless case where irreversibility has an important role and a large-drift case where irreversibility is innocuous.

## 4.1 A comprehensive tax schedule

Following Summers (1981) and Abel (1982), we introduce a corporate tax system into the firm problem. It includes a corporate income tax $t^c$, deduction allowance $\xi^d$, personal income tax $t^p$, and capital gains tax $t^g$.[21]

The firm pays the corporate income tax rate $t^c$ on its cash flow $Ay_s$ net of deductions $\xi^d k_s$, where $\xi^d$ denotes the deduction rate. Since the physical and the legal depreciation rates differ, we distinguish deductions from the capital stock and denote these with $d_s$. The state space now

[21] This taxation schedule is also used in the investment models by Poterba and Summers (1983); King and Fullerton (1984); Auerbach (1986); Auerbach and Hines (1986); Hassett and Hubbard (2002).

includes deductions $V(k,u,d)$. The corporate income tax and deductions jointly determine the after–tax profit rate

$$\pi_s \;=\; Ay_s - t^c(Ay_s - \xi^d d_s) \;=\; (1-t^c)Ay_s + t^c\xi^d d_s, \tag{52}$$

and the evolution of deductions[22]

$$\log d_s \;=\; \log d_0 - \xi^d s + \sum_{h:T_h\le s}\left(1+\frac{\theta_{T_h}+p(i_{T_h})i_{T_h}}{d_{T_h^-}}\right). \tag{53}$$

The personal income tax $t^p$ and the capital gain tax $t^g$ alter the firms' discount factor. We assume that equity is purchased by a representative investor with access to a riskless bond with return $\rho$ per unit of time. Let $D_s$ be the dividend per share, $P_s$ the equity price per share, and $E_s = 1$ the number of shares, which we normalize to unity without loss of generality. From the investor's perspective, dividends and bond returns are taxed at the rate $t^p$, while capital gains arising from changes in equity prices are taxed at the rate $t^g$. For any dividend process, no-arbitrage implies equal after-tax returns:

$$(1-t^p)\rho\,\mathrm{d}s \;=\; (1-t^g)\frac{\mathbb{E}[\mathrm{d}P_s]}{P_s} \;+\; (1-t^p)\frac{D_s}{P_s}\,\mathrm{d}s. \tag{54}$$

Condition (54) pins down the time-0 value of the firm, which equals the equity price:

$$V(k_0,u_0,d_0) \;=\; P_0 \;=\; \frac{1-t^p}{1-t^g}\,\mathbb{E}_0\left[\int_0^\infty e^{-\rho\frac{1-t^p}{1-t^g}s}D_s\,\mathrm{d}s\right]. \tag{55}$$

This expression says that the firm maximizes the cum-dividends market value of equity $P_0$ using the investor's after-tax discount factor $\rho(1-t^p)/(1-t^g)$, as in Auerbach (1979). We follow the "tax capitalization" view of the dividend decision and consider dividends as residuals, equal to the cash flow $\pi_s$ net of investment and capital adjustment costs[23]

$$D_s\,\mathrm{d}s \;=\; \pi_s\,\mathrm{d}s - (\theta_s + p(i_s)i_s)\mathcal{D}(s=T_h), \qquad \mathcal{D}(\cdot)\sim \mathit{Dirac}. \tag{56}$$

Given the tax schedule, Lemma 3 characterizes the problem with corporate taxation. The strategy consists of defining the discounted value of deductions per unit of investment $z$ and using it to rewrite the 3-state problem as the 1-state problem with the capital-productivity ratio solved

[22] We assume that the fixed adjustment cost are capitalized and enter into the expression for deductions. We thank Jim Hines for helpful advice on this modelling assumption.

[23] In the previous sections without corporate taxes, the Modigliani-Miller theorem holds, that is, the firms' values and investment policies—and the implicit dividend policy—were independent of the capital structure. Introducing taxes, in principle, could break this independence (for example, under the trade-off theory of the capital structure, see Hines and Park, 2017). Nevertheless, following the arguments in Miller (1977), and more recently in Abel (2018), we continue working under the Modigliani-Miller paradigm.

before in Section 2.3, under four parametric changes and an additive term that reflects deductions.

**Lemma 3.** *Define the discounted value of deductions as*

$$z \equiv \frac{\xi^d}{\rho\frac{1-t^p}{1-t^g} + \xi^d} < 1. \tag{57}$$

*The firm value with taxes can be decomposed as:*

$$V(k,u,d) = \frac{1-t^p}{1-t^g}\left[uv(\hat{k}) + t^c z d\right], \tag{58}$$

*where* $v(\hat{k})$ *solves the investment problem in Lemma 2 with the following four parametric changes:*

$$A \to (1-t^c)A, \tag{59}$$

$$\rho \to \frac{(1-t^p)}{(1-t^g)}\rho, \tag{60}$$

$$\theta \to (1-t^c z)\theta, \tag{61}$$

$$p(\Delta\hat{k}) \to (1-t^c z)\, p(\Delta\hat{k}). \tag{62}$$

The parametric changes established in Lemma 3 highlight the different channels through which taxes affect the firm value and optimal policy. The corporate income tax $t^c$ directly affects after-tax profitability $A$ in (59). The personal income tax $t^p$ and the capital gains tax $t^g$ scale the discount factor $\rho$ in (60).[24] The discounted value of deductions $z$ affects the firm value through an income effect, as deductions increase additively the firm value in (58), and a substitution effect, as deductions promote investment by reducing the after-tax adjustment costs and after-tax prices in (61) and (62). Additionally, $t^p$ and $t^g$ operate indirectly through $z$. Next, we formalize the channels through which taxes affect investment through their interaction with investment frictions.

### 4.2 Frictionless and frictional effects of corporate taxation

Proposition 5 decomposes the optimal investment policy into a neoclassical frictionless component and a dynamic component that comprises the investment frictions. It shows that, from a firm's perspective, what matters for investment decisions is the fixed cost and the price wedge relative to *after-tax* profits. To simplify the notation, we define the *after-tax* discount $\tilde{r}$ and the *after-tax*

[24] The factor $(1-t^p)/(1-t^g)$ also scales $A$, $\theta$, and $p(\hat{k})$. However, these parameters divide each other in all the expressions that follow, so we can safely ignore this factor.

user cost of capital $\tilde{\mathcal{U}}$ as:

$$\tilde{r} \equiv \frac{1-t^p}{1-t^g}\rho - \mu - \frac{\sigma^2}{2}, \tag{63}$$

$$\tilde{\mathcal{U}} \equiv \frac{1-t^p}{1-t^g}\rho + \xi^k - \sigma^2. \tag{64}$$

In particular, the after-tax user cost $\tilde{\mathcal{U}}$ is determined by the the personal income and capital gains taxes, the discount rate, the depreciation rate, and idiosyncratic volatility. For the problem to be well-defined, we assume $\tilde{r} > 0$ and $\tilde{\mathcal{U}} > 0$.

**Proposition 5.** *Let $\mathcal{K} \equiv \{\hat{k}^-, \hat{k}^{*-}, \hat{k}^{*+}, \hat{k}^+\}$ denote the firms' optimal investment policy characterized in Lemma 2. Consider the static log capital-productivity ratio $\hat{k}^{ss}$ that firms would set in the absence of the fixed cost and the price wedge:*

$$\hat{k}^{ss} = \frac{1}{1-\alpha}\log\left(\frac{1-t^c}{1-t^c z}\,\frac{\alpha A}{p\tilde{\mathcal{U}}}\right). \tag{65}$$

*With the static policy $\hat{k}^{ss}$, define the effective fixed cost $\tilde{\theta}$ (scaled by the after-tax static profits) and the effective prices $\tilde{p}^{sell}$ and $\tilde{p}^{buy}$ (scaled by the after-tax static profit-capital ratio):*

$$\tilde{\theta} \equiv \frac{1-t^c z}{1-t^c}\frac{\theta}{Ae^{\alpha\hat{k}^{ss}}}, \tag{66}$$

$$(\tilde{p}^{buy}, \tilde{p}^{sell}) \equiv \frac{1-t^c z}{1-t^c}\frac{(p^{buy}-p, p^{sell}-p)}{Ae^{(\alpha-1)\hat{k}^{ss}}}. \tag{67}$$

*Consider the normalized capital-productivity ratio $x \equiv \hat{k} - \hat{k}^{ss}$. Then the optimal investment policy can be decomposed as the sum of a static and a dynamic component*

$$\mathcal{K} = \hat{k}^{ss} + \mathcal{X}, \tag{68}$$

*where the dynamic component $\mathcal{X} \equiv \{x^-, x^{*-}, x^{*+}, x^+\}$ solves the following stopping problem:*

$$\mathcal{V}(x) = \max_{\tau,\Delta x} \mathbb{E}\Bigg[\int_0^\tau e^{-\tilde{r}\tau}\left(e^{\alpha x_s} - \alpha e^{x_s}\right)\mathrm{d}s + e^{\tilde{r}\tau}\left(-\tilde{\theta} + \tilde{p}(\Delta x)(e^{x_\tau+\Delta x} - e^{x_\tau}) + \mathcal{V}(x_\tau + \Delta x)\right)\Bigg| x_0 = x\Bigg], \tag{69}$$

$$\mathrm{d}x_t = -\nu\,\mathrm{d}t + \sigma\,\mathrm{d}W_t, \tag{70}$$

$$\tilde{p}(\Delta x) = \tilde{p}^{buy}\mathbb{1}_{\{\Delta x>0\}} + \tilde{p}^{sell}\mathbb{1}_{\{\Delta x<0\}}. \tag{71}$$

Proposition 5 provides several insights regarding the effects of corporate taxation on investment. The static optimal policy $\hat{k}^{ss}$ in (65) sets the capital-productivity ratio to a constant, and its value reflects after-tax profitability $(1-t^c)\alpha A$, the average after-tax user cost of capital $\tilde{\mathcal{U}}$ in (64), and the average after-tax investment price $(1-t^c z)p$. Studying the effects of corporate taxes on a frictionless investment policy and its implications for aggregate capital accumulation have been widely studied (see Summers, 1981, for early work).

By definition, investment frictions do not affect the static choice $\hat{k}^{ss}$. In contrast, the dynamic policy $\mathcal{X}$ characterized by (69), (70), and (71) takes into account the fixed cost and the price wedge, but these frictions enter scaled by after-tax static profits or by after-tax profit-capital ratio (recall the definition of effective frictions in (66) and (67)). Moreover, the flow payoff in the dynamic problem $e^{\alpha x_s} - \alpha e^{x_s}$ only depends on the curvature of the profit function $\alpha$, and thus it is tax invariant. Together, these observations imply that taxes have effects on the dynamic component $\mathcal{X}$ of the optimal policy exclusively through the effective investment frictions.

The fact that *after-tax* frictions are the key determinants for investment puts forward a novel channel for policy intervention: Corporate tax policy can change the effective size of fixed adjustment costs and the price wedge—technological constraints typically considered outside the control of a policymaker—and thus affect the dynamic component of investment. Proposition 6 formalizes the channels through which the corporate tax schedule shapes firm investment and signs the relationships with investment frictions.

**Proposition 6.** *The effective fixed cost $\tilde{\theta}$ and effective price wedge $\tilde{p}^{buy} - \tilde{p}^{sell}$ relate to the fundamental frictions as follows:*

$$\tilde{\theta} = \left(\frac{1-t^c z}{1-t^c}\frac{1}{A}\right)^{\frac{1}{1-\alpha}} \left(\frac{p\tilde{\mathcal{U}}}{\alpha}\right)^{\frac{\alpha}{1-\alpha}} \theta, \tag{72}$$

$$\tilde{p}^{buy} - \tilde{p}^{sell} = \frac{\alpha}{\tilde{\mathcal{U}}}\,\frac{p^{buy} - p^{sell}}{p}. \tag{73}$$

*If $t^c > 0$ and $\tilde{\mathcal{U}} > 0$, corporate taxes have the following effects on the after-tax investment frictions:*

1. *The effective fixed costs $\tilde{\theta}$ increases with $t^c$ and $t^g$; it decreases with $\xi^d$ and $t^p$.*

2. *The effective price wedge $\tilde{p}^{buy} - \tilde{p}^{sell}$ increases with $t^p$ and decreases with $t^g$. It does not change with $t^c$ or $\xi^d$ as long as $p = \overline{\mathbb{E}}[p(\Delta\hat{k})]$ is fixed.*

We focus the explanation on the effects of the corporate income tax. We derive three lessons from Proposition 6. First, a higher corporate income tax $t^c$ reduces profits and therefore increases the effective fixed cost that are scaled by after-tax profits. This effect is mediated by the depreciation allowance rate, being lowest when $z = 1$ (in this case $t^c$ is a pure profit tax) and highest when $\xi^d = z = 0$.

Second, the corporate income tax $t^c$ does not affect the effective price wedge as long as the average price $p$ remains fixed. This is because the profit-capital ratio $(1-t^c)Ae^{(\alpha-1)\hat{k}^{ss}}$ that divides the price wedge is invariant to $t^c$ as $t^c$ also enters the static policy $\hat{k}^{ss}$. If the average price $p$ does change, which would only happen if the relative shares of upward and downward adjustments react to the tax, then the effective price wedge would change as well. However, this effect is second order and quantitatively small.

And third, the effective fixed cost $\tilde{\theta}$ in (72) equals the fixed cost $\theta$ scaled by $(1 - t^c z)/(1 - t^c)$, and its derivative with respect to $t^c$ is increasing in $\theta$ (for $z < 1$):

$$\tilde{\theta} \propto \left(\frac{1 - t^c z}{1 - t^c}\right)^{\frac{1}{1-\alpha}} \theta. \tag{74}$$

This result suggests that cross-sectional differences in $\theta$ (say across firms, industries, or sectors) bring heterogenous responses to an identical change in $t^c$ across the board. In particular, industries with large fixed costs should be very sensitive to tax reforms; correspondingly, industries with zero fixed costs should be the ideal control group.[25] These observations offer a complementary identification strategy that exploits ex-ante heterogeneity instead of heterogeneity in the treatment.

In summary, to study the effects of corporate taxation on the macroeconomy, one can separate the static and dynamic components; and to study the dynamic component, it suffices to assess how corporate taxes change the effective investment frictions.

## 4.3 Two benchmark cases

The dynamic policy $\mathcal{X}$ solves the stopping time problem in (69) which closely resembles the price-setting and investment problems with fixed costs, analyzed first by Barro (1972), Sheshinski and Weiss (1977), Dixit (1991), but with the addition of a price wedge. We leverage on this work to characterize analytically the effect of taxes on individual policies and aggregate outcomes, extending previous results to the case with partial irreversibility. We consider two benchmark cases that isolate different mechanisms at play. Specifically, we show that the relative size of frictions matters and that the role of the price wedge crucially depends on the size of the drift. In what follows, recall that we now work with normalized capital-productivity ratios $x \equiv \hat{k} - \hat{k}^{ss}$.

**Zero drift.** We begin by characterizing the investment policy and the macroeconomic outcomes in driftless environments, that is, with zero drift and a symmetric price wedge. In this case, we demonstrate that capital misallocation ($\mathbb{V}ar[x]$) is a sufficient statistic for the role of corporate taxation on capital valuation ($q$) and capital fluctuations (CIR). Additionally, these driftless and symmetric environments clearly showcase the role of irreversibility. Specifically, the price wedge constitutes an important friction as firms expect to purchase and sell capital with equal probability.

[25] Alternatively, cross-sectional differences in depreciation allowances $z$, as documented in House and Shapiro (2008) and Zwick and Mahon (2017), should bring heterogenous responses to $t^c$, controlling for fixed costs. We thank Thomas Winberry for pointing out this observation.

As in Figure III, we consider three cases: only fixed cost, only price wedge, and both frictions. Proposition 7 characterizes these cases with a second-order approximation to the profit function.

**Proposition 7.** *Assume $\nu \to 0$ and symmetric effective price deviations $\tilde{p}^{buy} = -\tilde{p}^{sell} = \tilde{p}$. Without drift, the after-tax user cost of capital is $\tilde{\mathcal{U}} = \frac{1-t^p}{1-t^g}\rho - \sigma^2$ and the after-tax discount factor is $\tilde{r} = \frac{1-t^p}{1-t^g}\rho - \sigma^2/2$. In all symmetric cases we have: $\mathbb{E}[x] = 0$, $\mathbb{E}[\hat{k}] = \hat{k}^{ss}$ and $\mathbb{C}ov[x, a] = 0$.*

*(i)* ***Only fixed cost:*** *The inaction thresholds are $\bar{x} = \pm\left(\frac{6\tilde{\theta}\sigma^2}{\alpha(1-\alpha)}\right)^{1/4}$, the reset point is $x^* = 0$, and the macro outcomes are:*

$$\text{(75)} \qquad \mathbb{V}ar[x] = \frac{\overline{x}^2}{6}; \qquad q = 1 - \frac{\tilde{\mathcal{U}}}{\tilde{r}}\frac{\alpha(1-\alpha)}{2}\mathbb{V}ar[x]; \qquad \frac{CIR(\delta)}{\delta} = \frac{\mathbb{V}ar[x]}{\sigma^2}.$$

*(ii)* ***Only price wedge:*** *The inaction thresholds and reset points coincide $\overline{x}^* = \pm\left(\frac{3\tilde{p}\sigma^2}{2\alpha(1-\alpha)}\right)^{1/3}$, and the macro outcomes are:*

$$\text{(76)} \quad \mathbb{V}ar[x] = \frac{\overline{x}^{*2}}{3}; \quad q = 1 - \left(1 + \frac{2}{\alpha}\right)\frac{\tilde{\mathcal{U}}}{\tilde{r}}\frac{\alpha(1-\alpha)}{2}\mathbb{V}ar[x]; \quad \frac{CIR(\delta)}{\delta} = \left(1 + \frac{1}{\sigma^2}\right)\mathbb{V}ar[x].$$

*(iii)* ***Both frictions:*** *The thresholds of the inaction region $\pm\overline{x}$ and the reset points $\pm x^*$ solve:*

$$\text{(77)} \quad \overline{x}x^*(\overline{x} + x^*) = \frac{3\tilde{p}\sigma^2}{\alpha(1-\alpha)}; \qquad \overline{x}^4 - x^{*4} = \frac{3\tilde{p}\sigma^2}{\alpha(1-\alpha)}(\overline{x} - x^*)(1 + \overline{x} + x^*) + \frac{6\tilde{\theta}\sigma^2}{\alpha(1-\alpha)},$$

*and the macro outcomes are:*

$$\text{(78)} \qquad \mathbb{V}ar[x] = \frac{\overline{x}^2 + x^{*2}}{6}$$

$$\text{(79)} \qquad q = 1 - \frac{\tilde{\mathcal{U}}}{\tilde{r}}\frac{\alpha(1-\alpha)}{2}\left(\mathbb{V}ar[x] + \frac{2}{\alpha}\frac{\overline{x}x^*}{3}\right)$$

$$\text{(80)} \qquad \frac{CIR(\delta)}{\delta} = \frac{\mathbb{V}ar[x]}{\sigma^2} + \frac{x^*\overline{x}}{3}.$$

*When only one friction is active, a marginal increase in the other friction has no effect on the macro outcomes:*

$$\text{(81)} \qquad \left.\frac{\mathrm{d}\mathbb{V}ar[x]}{\mathrm{d}\tilde{p}}\right|_{\tilde{\theta}>0,\,\tilde{p}=0} = 0; \quad \text{and} \quad \left.\frac{\mathrm{d}M}{\mathrm{d}\tilde{\theta}}\right|_{\tilde{\theta}=0,\,\tilde{p}>0} = 0, \quad \text{for} \quad M \in \{\mathbb{V}ar[x], q, CIR\}.$$

When only one friction is active, in cases (*i*) and (*ii*), there is a positive relationship between the corresponding effective investment friction ($\tilde{\theta}$ or $\tilde{p}$) and capital misallocation $\mathbb{V}ar[\hat{k}]$. This relationship results from the expressions for the inaction region and the cross-sectional variance. In turn, higher misallocation reduces $q$ by lowering aggregate productivity $\hat{Y}/\hat{K}$, and increases the

CIR, slowing down the propagation of aggregate productivity shocks. If effective frictions were of the same size, that is $\tilde{\theta} = \tilde{p}$, expressions (75) and (76) reveal that a price wedge generates a higher $\mathbb{V}ar[x]$, a lower $q$, and a larger CIR compared to the case with only fixed costs.

Now let us discuss case (*iii*) in which both frictions are present. In this case, the sufficient statistics for $q$ and CIR are misallocation $\mathbb{V}ar[x]$ and the product $\overline{x}x^*$. When $\overline{x} \approx x^*$ this product is proportional to $\mathbb{V}ar[x]$ (as in the case with only partial irreversibility). The first observation is that the inaction region $(-\overline{x}, \overline{x})$ and the reset points $\{-x^*, x^*\}$ are jointly determined by the size of both frictions. Frictions have opposing effects on the within and between components of misallocation, so the effect on the total misallocation is ambiguous. When the price wedge is positive, introducing a fixed cost shrinks the distance between the two reset points, reducing between variance. When the fixed costs is positive, introducing a price wedge generates two different reset points, increasing the between variance. In the limits where only one friction is active, the result in (81) teaches us that a marginal increase in the other friction has no effect on the macro outcomes (recall our earlier discussion around Figure III).

**Large drift.** Next we characterize the case with a large drift relative to idiosyncratic shocks. In this case, we demonstrate that the price wedge is irrelevant. The reason is that firms upsize by actively purchasing capital but downsize by letting the drift shrink its capital-productivity ratio. Thus the purchase price $\tilde{p}^{buy}$ is the only relevant price. Proposition 8 shows this result.[26]

**Proposition 8.** *Let $\nu > 0$ and $\sigma^2 \to 0$ such that $\nu/\sigma^2 \to \infty$. In this case, the after-tax user cost is $\tilde{\mathcal{U}} = \frac{1-t^p}{1-t^g}\rho + \xi^k$ and the after-tax discount is $\tilde{r} = \frac{1-t^p}{1-t^g}\rho - \mu$. The policy is a one-sided inaction region with lower threshold $x^-$ and one reset point $x^*$. The cross-sectional distribution is Uniform over $[x^-, x^*]$ with moments:*

$$(82) \qquad \mathbb{E}[x] \;=\; \frac{(x^* + \overline{x})}{12}; \qquad \mathbb{V}ar[x] \;=\; \frac{(x^* - \overline{x})^2}{12}.$$

*The policy solves the non-linear system*

$$(83) \qquad \mathbb{E}[x]\sqrt{\mathbb{V}ar[x]} \;=\; -\frac{\tilde{r}\tilde{\theta}}{\sqrt{12}\alpha(1-\alpha)}; \qquad \frac{\mathbb{E}[x]}{\mathbb{V}ar[x] + \mathbb{E}[x]^2} \;=\; -\left(\frac{\tilde{r}}{\nu} + \frac{\alpha+1}{2}\right),$$

*and the macro outcomes are*

$$(84) \qquad q \;=\; 1 \;-\frac{\tilde{\mathcal{U}}}{\tilde{r}}(1-\alpha)\left(\mathbb{E}[x] + \frac{\alpha}{2}\mathbb{V}ar[x]\right); \qquad \frac{CIR(\delta)}{\delta} \;=\; 0.$$

The case with a large drift reveals new mechanisms absent in symmetric environments. As we have already mentioned, the price wedge has no effect. Comparing the expression for aggregate

[26] Instead of taking the drift to infinity, we take an equivalent limit towards zero idiosyncratic shocks.

$q$ and the CIR with large drift against the three driftless cases in Proposition 7, we see how the average $\mathbb{E}[x]$ now matters in this environment. Moreover, it is the frictional average $\mathbb{E}[x]$ and not the frictionless average $\mathbb{E}[\hat{k}]$ the relevant statistic for the marginal value of capital. The non-linear system in (83) that pins down the investment policy shows that larger effective fixed costs $\tilde{\theta}$ increase both the average $\mathbb{E}[x]$ (in absolute value) and the variance $\mathbb{V}ar[x]$ of the normalized capital-productivity ratios $x$. In fact, the first equation is an indifference curve that mediates the trade-off between these two moments.[27] The same system shows that the average $\mathbb{E}[x]$ is negative, thus $\mathbb{E}[\hat{k}] = \hat{k}^{ss} + \mathbb{E}[x] < \hat{k}^{ss}$. As the mean becomes more negative, $q$ goes up; but as the variance increases, $q$ goes down. The overall effect depends on the relative elasticities of these moments with respect to $\tilde{\theta}$. Lastly, as shown in Corollary 2 of Baley and Blanco (2021), the CIR equals zero: aggregate productivity shocks are immediately absorbed by firms and there are no deviations from steady-state.

The benchmark cases with zero and large drift teach us two lessons. First, the importance of the effective price wedge (and the taxes that shape it) crucially depends on the drift. Without drift, the price wedge is an important source of misallocation; in environments with large drift relative to idiosyncratic shocks, it is not. Second, the effect of taxes on $q$ depend on the relative size of the mean $\mathbb{E}[x]$ and the variance $\mathbb{V}ar[x]$ of normalized capital-productivity ratios. In symmetric environments, the mean is zero and thus higher misallocation always decreases $q$. With a large drift, the mean is negative, reflecting capital scarcity. Scarcity increases $q$ and could in principle dominate the misallocation effect that reduces $q$.

# 5 Empirical application

In this section, we put the theory to work. The goal is to examine the macroeconomic consequences of a shift from a high to a low tax corporate tax regime. We use microdata to discipline the magnitude of the various forces identified in the theory and predict the direction in which the capital measures will move. We do this in two steps. First, we discipline the size of investment frictions and quantify the different forces through which corporate taxes operate. To do this, we use Chilean investment micro data leveraging on the fact that the Chile has several advantages to evaluate our theory (as described next). Second, we use the calibrated model to conduct comparative statics across steady-states focusing on changes to the corporate income tax rate.

## 5.1 Data description

Using Chilean data has several advantages to apply our theory. Chile is a small open economy

[27] A larger fixed cost lengthens the inaction period and firms accumulate more drift, reducing the average capital-productivity ratio relative to a frictionless economy. As firms anticipate a larger drift, they increase the reset point widening the distance between $x^-$ and $x^*$, increasing the variance.

with an exogenous interest rate, as our theory assumes. Chile does not feature a specific tax on capital gains $t^g$, which are taxed at the personal income tax rate $t^p$. As these rates are identical, the ratio $(1-t^p)/(1-t^g)$ equals one and does not affect the discount factor. Moreover, depreciation deductions $z$ in Chile in our sample period are very small relative to other OECD countries (Asen, 2020). A low $z$ amplifies the effects of the corporate income tax $t^c$ on the effective fixed costs, as discussed in Proposition 6. Finally, the corporate income tax rate has fluctuated considerably in the last four decades. Appendix E provides all the details on the data.

**Data sources.** We use yearly investment data on manufacturing plants in Chile from the Annual National Manufacturing Survey (*Encuesta Nacional Industrial Anual*) for the period 1980 to 2011. To construct the capital series, we use information on depreciation rates and price deflators from Chilean national accounts and Penn World Tables. The sample considers plants that appear in the sample for at least 10 years (more than 60% of the sample) and have more than 10 workers. Data on the corporate income tax comes from Vegh and Vuletin (2015), which we cross-checked and updated using several sources.

**Capital stock and investment rates.** We construct the capital stock series using the perpetual inventory method. We include structures, machinery, equipment, and vehicles. Following the theory, a plant's capital stock in year $s$, $k_s$, evolves as

$$k_s = (1-\xi^k)k_{s-1} + I_s/(p(I_s)D_s), \tag{85}$$

where $\xi^k$ is the physical depreciation rate; $I_s$ is the nominal value of investment; $p(I_s)$ is the investment pricing function, which considers different prices for capital purchases and sales; $D_s$ is the gross fixed capital formation deflator, and $k_0$ is a plant's self-reported nominal capital stock at current prices for the first year in which it is nonnegative. Note that the ratio $I_s/(p(I_s)D_s)$ is the real investment in capital units (the data counterpart to $i_s = \Delta k_s$ in the model). We set a price wedge of 5%, which is an intermediate value in the literature.[28]

We construct gross nominal investment $i_s$ with information on purchases, reforms, improvements, and sales of fixed assets, and define the investment rate $\iota_s$ as the ratio of real gross invest-

[28] Ramey and Shapiro (2001) study the reallocation of capital previously operated by closing aerospace plants. They find a discount of 0.28 cent per dollar. Khan and Thomas (2013) set a discount of 0.03 cent per dollar and Lanteri, Medina and Tan (2020) set a discount of 0.07 cent per dollar. Kermani and Ma (2020) document much lower liquidation recovery rates consistent with very high average levels of asset specificity. We set a value of 0.05 which lies in between these studies. Note that only the price wedge matters for computing investment, not the price level.

ment to the capital stock:[29]

$$\iota_s \equiv \frac{I_s/(p(I_s)D_s)}{k_{s-1}}. \tag{86}$$

**Variable construction.** For each plant and each inaction spell $h$, we record the change in the capital-productivity ratio upon action $\Delta\hat{k}_h$ and the spell's duration $\tau_h$. We construct $\Delta\hat{k}_h$ with investment rates from (86):

$$\Delta\hat{k}_h = \begin{cases} \log(1+\iota_h) & \text{if} \quad |\iota_h| > \underline{\iota}, \\ 0 & \text{if} \quad |\iota_h| < \underline{\iota}. \end{cases} \tag{87}$$

The threshold $\underline{\iota} > 0$ reflects the idea that small maintenance investments should be excluded. Following Cooper and Haltiwanger (2006), we set $\underline{\iota} = 0.01$, such that all investment rates below 1% in absolute value are considered to be part of an inaction spell. Then we define an adjustment date $T_h$ from $\Delta\hat{k}_{T_h} \neq 0$ and compute a spell's duration as the difference between two adjacent adjustment dates: $\tau_h = T_h - T_{h-1}$. Finally, we truncate the investment distribution at the 2nd and 98th percentiles to eliminate outliers.[30]

Figure V plots the resulting cross-sectional distribution of non-zero changes of the capital-productivity ratios $\Delta\hat{k}$ and completed inaction spells $\tau$, conditional on a past positive or negative investment. The data shows investment patterns that are consistent with partial irreversibility. In particular, the distribution of investment conditional on a last negative investment $H^+(\Delta k)$ is skewed toward the left of the distribution conditional on a last positive investment $H^-$, meaning that the probability of a negative investment is larger after a negative investment and vice versa.

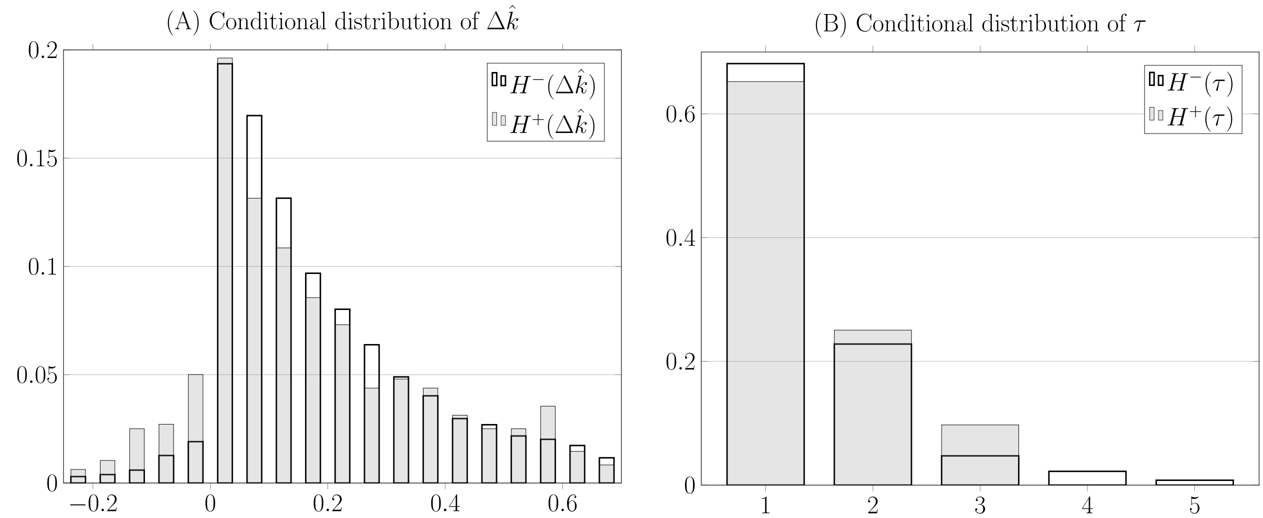
### 5.2 Aggregate capital behavior: 1980-2011

With the microdata at hand, we now assess the nature and size of investment frictions and the magnitude of the various mechanisms that shape aggregate capital behavior. There are several parameters that we calibrate externally before applying the theoretical mappings to recover the capital behavior from the microdata. These parameters include taxes, the discount factor, technological constants, and investment prices. We set these parameters to match average statistics from the Chilean economy between 1980 and 2011. The parameterization is summarized in Table I.

[29] Note that the investment rate equals $\iota_{T_h} \equiv i_{T_h}/k_{T_h^-} = (k_{T_h} - k_{T_h^-})/k_{T_h^-}$, where $k_{T_h^-} = \lim_{s\uparrow T_h} k_s$. In contrast to the continuous-time model, in which investment is computed as the difference in the capital stock between two consecutive instants, in the data we compute it as the difference between two consecutive years.

[30] Table I in the Data Appendix presents descriptive statistics on investment rates. In particular, the inaction rate ($|\iota| < 0.01$) equals 40.1%.

**Figure V** – Empirical Distribution of Observable Actions




Notes: Own calculations using establishment data from Chile. Panel A plots the distribution of *non-zero* changes in capital-productivity ratios and Panel B plots the duration of inaction spells. Solid bars = conditional on departing from $\hat{k}^{*+}$ (last negative investment); white bars = conditional on departing from $\hat{k}^{*-}$ (last positive investment). Sample: Firms with at least 10 years of data, truncation at 2nd and 98th percentiles of investment rate distribution, and inaction threshold of $\underline{\iota} = 0.01$.

**Externally-calibrated parameters.** One period equals a year. We set the real interest rate to 6.6% ($\rho = 0.066$) to match the average real interest rate computed by the IMF. The productivity growth rate is 3.3% ($\mu = 0.033$) to match the average GDP growth rate. The returns-to-scale parameter is $\alpha = 0.72$ to match an elasticity of output to capital of 0.3 taking into account labor.[31] We set investment prices to $p^{\text{buy}} = 2$ and $p^{\text{sell}} = 1.90$ to match an average aggregate output-capital ratio of $\hat{Y}/\hat{K} = 0.36$ and an irreversibility wedge of 5% as above. Finally, we normalize $A = 1$.

**Taxes.** We set the tax schedule to match the average values in Chile between 1980 to 2011. The personal income and capital gain tax rates are identical and equal to $t^p = t^g = 0.471$. We set the depreciation deduction rate to $\xi^d = 0.07$ to match the PDV of depreciation allowances under the Chilean straight-line system. Lastly, the corporate income tax rate (the highest marginal rate) is on average $t^c = 0.26$ during the sample period. The implied PDV of deductions is $z = 0.547$.

**Estimated parameters.** Using the mappings from the microdata to the parameters of the productivity process in (31) and (32), we recover a drift of $\nu = 0.118$ and a volatility of $\sigma^2 = 0.054$. Together with the productivity growth rate, the value for the drift $\nu$ implies a physical

[31] To set this parameter, we consider a generalized production function that includes labor $l$ as a frictionless input, $y = u^{1-\eta\tilde{\alpha}}\left(k^{\tilde{\alpha}} l^{1-\tilde{\alpha}}\right)^{\eta}$. Static maximization over labor implies $y \propto k^{\frac{\eta\tilde{\alpha}}{1-(1-\tilde{\alpha})\eta}}$. Assuming standard parameters in the literature, $\eta = 0.90$ and $\tilde{\alpha} = 0.3$, the implied value for the output-capital elasticity is $\alpha = (\eta\tilde{\alpha})/(1-(1-\tilde{\alpha})\eta) = 0.72$.

**Table I** – Parametrization

| Taxes | | | | | Technology | | | | | Productivity | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\tau^p$ | $\tau^g$ | $\tau^c$ | $\xi^d$ | $z$ | $\mu$ | $\alpha$ | $\rho$ | $p^{\text{buy}}$ | $p^{\text{sell}}$ | $\nu$ | $\sigma^2$ |
| 0.471 | 0.471 | 0.260 | 0.070 | 0.547 | 0.033 | 0.720 | 0.066 | 2.000 | 1.900 | 0.118 | 0.054 |

Notes: Baseline parameterization of the model. Average tax rates in Chile in the period 1980-2011. Other parameters are set externally or recovered from the microdata through the lens of the theory, see text for details.

depreciation rate of $\xi^k = \nu - \mu = 0.085$. Given these values, the implied after-tax discount is $\tilde{r} = \rho - \mu - \sigma^2/2 = 0.006$ and the after-tax user cost is $\tilde{\mathcal{U}} = \rho + \xi^k - \sigma^2 = 0.097$.

**Putting the theory to work.** We are ready to assess the nature and magnitude of investment frictions and the role of the various forces in shaping the average macro outcomes. Table II shows the average investment policy and macro outcomes in Chile for the period between 1980 and 2011.

We begin by examining the investment policy. From (33) and (34), we recover the gap between the two reset points, $\hat{k}^{*+} - \hat{k}^{*-} = 0.372$, is a tell-tale sign of partial irreversibility.[32] This gap is almost equally explained by the exogenous price wedge, $\log(p^{\text{buy}}/p^{\text{sell}}) = 0.183$, and the endogenous behavior of firms reflected in the PDV of the capital-productivity ratio 0.189 (computed as a residual). Next, we recover the average macro outcomes during the sample period.

**Table II** – Aggregate Capital Behavior

| **Investment Policy** | | **Capital Allocation** | |
|---|---|---|---|
| Difference in reset capitals ($\hat{k}^{*+} - \hat{k}^{*-}$) | 0.372 | Variance | 0.099 |
| Exogenous price wedge | 0.183 | Within | 0.067 |
| PDV of capital-productivity ratio | 0.189 | Between | 0.032 |
| **Capital Valuation** | | **Capital Fluctuations** | |
| Tobins $q$ | 1.041 | CIR | 2.509 |
| Productivity | 1.050 | Variance | 1.821 |
| Irreversibility | -0.009 | Covariance | 0.604 |
| | | Irreversibility | 0.083 |

Notes: Objects recovered from theory mappings applied to establishment-level data from Chile. Parameters described in Table I.

Using (35) and (36), we estimate an average misallocation of $\mathbb{V}ar[\hat{k}] = 0.099$, where 67% comes from within-dispersion and 33% comes from between-dispersion driven by the price wedge (this implies that ignoring the price wedge underestimates misallocation in at least 33%). We use (40) to recover an average capital valuation of $q = 1.041$. While $q$ is not far from its frictionless value

[32] Caballero and Engel (2007) and Lanteri, Medina and Tan (2020) propose complementary methodologies to diagnose the pervasiveness of irreversibility in capital reallocation.

(unity), it would be erroneous to conclude that dynamic frictions are not present; in fact, they are both important but compensate one another. The productivity component in (41) is 1.050 and the irreversibility component in (42) is $-0.009$. As predicted by the theory, irreversibility decreases $q$. Lastly, using (49), we recover an average CIR of 2.509, meaning that a 1% decrease in aggregate productivity generates a total deviation of aggregate capital above its steady-state value of 2.5% (that is, the average multiplier of productivity shocks is 2.5).

We further decompose the CIR into its three components: variance 1.821 from (36), covariance 0.604 from (50), and irreversibility 0.083 from (51). As predicted by the theory, the CIR's irreversibility term is positive; however, it is quantitatively small and most of its effects operate indirectly by increasing the steady-state moments. This observation implies that irreversibility operates primarily by reducing the sensitivity to idiosyncratic shocks (increasing $\mathbb{V}ar[\hat{k}]$) and increasing the relative cost of downsizing the capital stock (increasing $\mathbb{C}ov[\hat{k}, a]$).

### 5.3 A regime shift from high to low taxes

This section explores the macroeconomic effects of a regime shift from high to low taxes, focusing on the corporate income tax rate.[33] We motivate this exercise with the observation that the top marginal corporate income tax rate experienced a median drop of 17 percentage points across OECD countries, from 42% in 1980 to 25% in 2020.[34]According to the theory, a decline in the corporate income tax rate is equivalent to a reduction in the after-tax fixed cost. While this reform should have unambiguously reduced misallocation, other things equal, the consequences for capital valuation and capital fluctuations depend on the magnitude of the various counteracting forces that we characterized in Section 4.

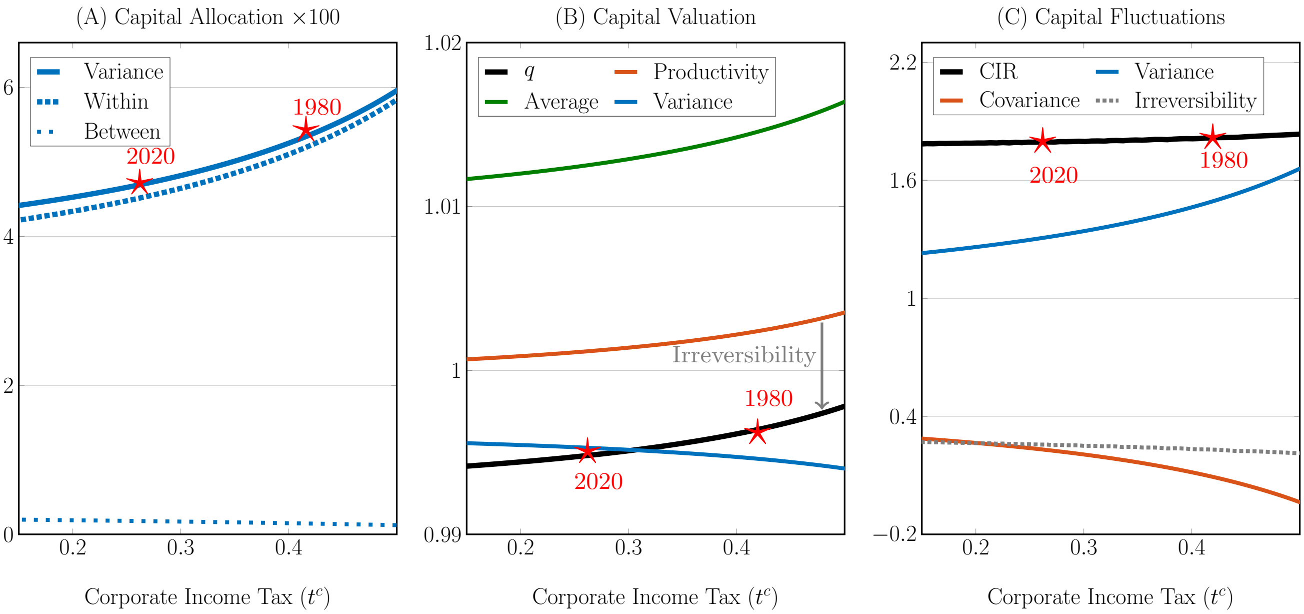
To discipline these forces, we use the parameterization that matches the average Chilean experience summarized in Table I. Additionally, we must take a stand on the size of the fixed cost $\theta$ in order to map the changes in the corporate tax into changes in the after-tax fixed cost $\tilde{\theta}$ in (72). Note that taking a stand on the size of the fixed cost was not necessary for applying the mappings from microdata to macro outcomes in the previous section. Here, we search for a fixed-cost parameter using the method of moments to minimize the relative distance between two moments in the model and the data: the variance of capital-productivity ratios $\mathbb{V}ar[\hat{k}]$ and the covariance of capital-productivity ratios with the time elapsed since their last adjustment $\mathbb{C}ov[\hat{k}, a]$ (below we discuss these choices and the implied model fit). We obtain a fixed cost of $\theta = 0.2$.

Figure VI illustrates the macroeconomic consequences of a drop in the corporate tax rate. Panel A shows capital misallocation $\mathbb{V}ar[\hat{k}]$ (solid line) and its decomposition into within (dashed

[33] Appendix D conducts similar analysis for the other three tax instruments.

[34] In Chile, the evolution of the corporate tax rate is U-shaped. It was 40% in 1980, dropped to 10% in 1984, and then consistently (but infrequently) moved upward until reaching 20% in 2020 (see Appendix E). In this exercise, we identify the high-tax regime with 1980 and the low-tax regime with 2020.

**Figure VI** – Macro Outcomes in High (1980) and Low (2020) Tax Regimes




Notes: Panels A, B, and C show capital allocation, valuation, and fluctuations for various levels of the corporate income tax rate in the range $t^c \in [0.1, 0.5]$. Parameterization from Table I and fixed costs of $\theta = 0.2$. Stars correspond to the median values of the top corporate tax rate $t^c$ in the OECD: 1980 = 42%, 2020 = 25%.

line) and between (dotted line) variances following (37). In this parameterization with a relatively large drift, fixed costs are the primary investment friction and the within-variance is almost the only source of misallocation. We observe that a decline in the tax rate improves the allocation of capital. As predicted by equation (72) and Propositions 7 and 8, lower $t^c$ reduces the effective fixed cost $\tilde{\theta}$ and shrinks inaction regions, lowering firms' tolerance for mismatch between their capital and their productivity and decreasing the dispersion of capital-productivity ratios.

Panel B shows capital valuation $q$ (in black) and its decomposition into productivity (in orange) and irreversibility components according to (40). As predicted by the theory, the irreversibility term (marked with a downward arrow) is negative and reduces $q$ below 1 for all levels of $t^c$. We discover that $q$ moves in the same direction as the tax rate. To understand why this is the case, we use expression (84) and plot the two margins affecting productivity $\hat{Y}/\hat{K}$ in (41): the average (green) and the variance (blue) of centralized of capital-productivity ratios. When $t^c$ decreases, firms invest more and the average capital-productivity ratio $\mathbb{E}[\hat{k}]$ goes up. Abundant capital is less valuable and $q$ goes down. At the same time, the allocation of capital improves, $\mathbb{V}ar[\hat{k}]$ falls (see Panel A) and $q$ goes up. In this parameterization, the first effect dominates and $q$ follows $t^c$.

Panel C shows capital fluctuations measured by the CIR (in black) and decomposed into three terms following (49): variance (in blue), covariance (in orange), and irreversibility (in gray). The variance term reflects misallocation (see Panel A). The positive covariance term says that firms with old capital have a large desire to downsize, but they do not sell their capital to avoid the penalty of the price wedge. The positive irreversibility term increases the CIR beyond the sum of the other two terms. We find that the CIR also moves in line with the tax rate, meaning that aggregate productivity shocks propagate more quickly when taxes are low.[35] The variance and covariance terms move in opposite directions with $t^c$: the variance falls due to lower effective fixed costs $\tilde{\theta}$, whereas the covariance increases because the price wedge plays a larger role vis-à-vis the fixed costs. Overall, for this parameterization, the variance dominates and the CIR follows $t^c$.

In summary, this calibrated version of our parsimonious model suggests that a drop in the corporate income tax rate reduces capital misallocation, reduces capital valuation (due to a larger stock of capital), and accelerates the propagation of aggregate productivity shocks.

**A remark on the calibration of fixed costs.** Let us compare the values for the macro outcomes reported in Table II—recovered directly from the microdata mappings assuming an average corporate tax rate of $t^c = 0.26$—with the corresponding values in Figure VI—obtained by simulating the model. We see that all values in the data are consistently larger than those produced by the model. The reason for this discrepancy is that our model with a symmetric fixed cost is extremely parsimonious and cannot reproduce the large variance of capital-productivity ratios $\mathbb{V}ar[\hat{k}]$ and the large covariance of capital-productivity ratios and their age $\mathbb{C}ov[\hat{k}, a]$ recovered from the data. The simulated method of moments strikes a balance between these two moments in the data, but falls below their empirical values.

In previous work (Baley and Blanco, 2021), we demonstrated that the symmetric fixed cost model is unable to replicate the empirical values of these two moments and showed how it should be augmented in order to match them. Introducing a time-dependent component in adjustment, such as random opportunities for free adjustment, increases the variance $\mathbb{V}ar[\hat{k}]$. Introducing asymmetric fixed costs that depend on the adjustment sign increases the covariance $\mathbb{C}ov[\hat{k}, a]$ (the price wedge already pushes the variance up, but it is not quantitatively enough). Augmenting the model in these two directions is straightforward and necessary to conduct a fully-fledged quantitative analysis. Nevertheless, we have opted to keep the model as simple as possible to facilitate its exposition and to highlight the key mechanisms at work in the cleanest way.

# 6 Final remarks

We propose a new laboratory to study the macroeconomic effects of permanent corporate tax reforms. We find that reductions in the corporate income tax rate improve the allocation of capital across firms, which in turn reduces capital valuation and accelerates the capital response to productivity shocks.

We also put forward *after-tax investment frictions* as the appropriate notion to evaluate the

[35] The CIR goes down by 1.13% from 1.77 at $t^c = 0.42$ to 1.75 at $t^c = 0.25$.

effects of corporate tax reform; specifically, our theory predicts that sectors with higher fixed costs are more sensitive to tax reforms and thus experience a larger variation in aggregate capital measures following change in the corporate income tax rate. We leave for future work testing this prediction with cross-sectional data.

We foresee three avenues for developments that would extend the scope of our analysis. A first avenue broadens the notion of *after-tax frictions* to investigate the role of entry and exit, imperfect information, and other investment frictions that may interact with corporate taxation and distort the allocation of capital (David and Venkateswaran, 2019). A second avenue enriches the financial structure of the model, either by introducing financial frictions at the firm-level (Khan and Thomas, 2013; Kehrig and Vincent, 2019; Ottonello and Winberry, 2020) or considering general equilibrium effects (Khan and Thomas, 2008; Bachmann, Caballero and Engel, 2013; Winberry, 2021; Miao, 2019; Koby and Wolf, 2020). These additional financing channels could mitigate or exacerbate the economic forces put forward by our analysis. Lastly, a third avenue examines the transitional dynamics between two corporate tax regimes (Gourio and Miao, 2011), as well as the response of the monetary policy rate in shaping transitional dynamics.

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