Large Firms and Innovation-Led Growth

by

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Dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in the Department of Economics
in the Graduate School of Duke University
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Abstract

This dissertation consists of two self-contained essays on economic growth. Chapter 2, "Large firms and long-run growth" studies the effect of the rise in the market share of large firms on long and medium run productivity growth. The market share of large firms in the U.S. has been on the rise in the past three decades. This paper quantifies the effects of this change on labor productivity growth. It develops a tractable endogenous growth model with both large and small firms, and shows that as the market share of large firms increases, productivity growth first increases and then declines. This is due to the change in the incentive of large firms to do research and development (R&D). To validate this relationship, the paper uses a panel of U.S. industries and documents that the industry level R&D-intensity has an inverted-U relationship with the market share of large firms. To explore the macro implications of this mechanism, the paper calibrates the model to match the aggregate moments of the U.S. economy. The exercise shows that as the market share of large firms increased, productivity growth increased until the late nineties and then declined. An important implication of the model is that as the economy becomes more concentrated, recessions become deeper and recoveries become slower.

Chapter 3, "Implications of tax Policy for innovation and aggregate productivity growth" studies the effect of corporate and individual taxes on productivity growth. The quantitative implications of income taxation for innovation and aggregate productivity growth are evaluated in the context of a Schumpeterian model of innovation-led growth. In the model, innovation comes from entrant firms creating new products and from incumbent firms improving own existing products. The model embodies key features of the U.S. government sector: (i) an individual income (labor income, dividends, and capital gains) and (ii) corporate tax; (iii) a consumption tax; and (iv) government purchases. The model is further restricted to fit observations for the post-war U.S. economy. The results suggest that endogenous movements in TFP constitute a quantitatively important channel for the transmission of tax policy to real GDP growth. Endogenous market structure plays a key role in the propagation of tax shocks.

To Mahka for her unconditional support.

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Abbreviations

R&D	Research and Development.
MSOLF	Market Share of Large Firms.
ESOLF	Employment Share of Large Firms.
rdI	R&D Intensity
CCM	Compustat and CRISP Merged.
BDS	Business Dynamic Statistics.
SUSB	Statistics of U.S. Businesses.

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1

Introduction

This dissertation consists of two independent chapters. The introductions of the first and second chapters are in section 2.1 and 3.1, respectively.

2

Large Firms and Long-run Growth

2.1 Introduction

Recent policy papers (CEA, 2016; ERP, 2016) and academic studies (De Loecker and Eeckhout, 2017; Autor et al., 2017; Grullon et al., 2016; Bessen, 2016; Gutiérrez and Philippon, 2016; Arora et al., 2015) have raised concerns about too little competitive pressure on large firms in U.S. industries. This paper investigates the effect of the rise in the market share of large firms on labor productivity growth. It develops a tractable Schumpeterian endogenous growth model with both large and small firms, that produces analytically transparent transitional dynamics. It thus provides a framework to study the role of endogenous market structure in macroeconomic questions. Calibration of the model to aggregate moments of the U.S. economy shows that due to the rise in the market share of large firms, productivity growth increased until the late nineties, and declined since then. Importantly, as the market share of large firms increases, the recessions become deeper and the recoveries slower.

Empirical studies have documented that in the last three decades the size of large firms (Grullon et al., 2016), their profitability (Gutiérrez and Philippon, 2016), and the markups they charged (De Loecker and Eeckhout, 2017) have increased, while the entry rate (Pugsley and Sahin, 2015), R&D investment (Arora et al., 2015) and the labor share (Autor et al., 2017) have declined. These trends are important for policy makers and economists because they affect long run productivity growth. This paper provides a quantitative growth model that encompasses these trends and shows a clear causal relationship from changes in market structure to productivity growth. First, the paper documents that in line with recent studies on the increase in market concentration, aggregate measures of the share of large firms have been following an upward trend since the mid eighties. Next, the paper constructs a panel of U.S. industries to revisit and refine the empirical question about the inverted-U relation between R&D-intensity and competition (Cohen and Levin, 1989; Aghion et al., 2005). The paper validates a core ingredient of the model and shows that R&D-intensity (defined as industry R&D divided by industry sales) has a robust inverted-U relation with the employment share of large firms (defined as employment in large firms divided by total employment). Particularly, the paper addresses the problem of endogeneity by using the regulation index from Al-Ubaydli and McLaughlin (2017) as instrument for employment share of large firms, that allows a causality interpretation. These empirical evidence suggests that the increase in the market share of large firms caused a decline in the R&D-intensity of large firms during the 1985-2017 period.

Second, the equilibrium conditions of the model reduce to a single differential equation in terms of the market share of large firms (absent the external forces). Thus, the only endogenous state variable, *i.e.,* the market share of large firms follows its own dynamics, and other endogenous variables like the technology growth and the entry of new firms are determined by the state variable. Importantly, the paper shows that the technology growth has an *industry-specific time-invariant inverted-U* profile in market share of large firms.

This paper introduces the canonical industrial organization (IO) market structure of "dominant firm with a competitive fringe" (Scherer and Ross, 1990) to Schumpeterian creative accumulation growth models (Peretto, 1998). In each industry there exists a dominant (large) firm with positive market share that sets its own price, and takes into account its effect on industry price. Large firms produce differentiated *brand* products and have positive profits. Each large firm has a competitive fringe that is a continuous measure of small firms, producing a homogeneous *generic* product, which is an imperfect substitute for the brand product. The competitive fringe represent small firms in each industry, which have no market power individually and make zero profit. Large firms invest part of their profits in R&D and do process innovation. This lowers their marginal cost of production and results in increasing their market share within industries at the expense of small firms. In the literature, this is often known as the *business-stealing* effect (Mankiw and Whinston, 1986). When the share of large firms is small, it is easy to increase it by process innovation, but as the share of large firms increases, business-stealing becomes increasingly harder, because there are less and less shares out there to steal from. Thus, as the market share of large firms increases, the business-stealing mechanism lowers the return on R&D investment. The model also features the well-known positive Schumpeterian effect of market share on R&D-return. In particular, R&D can be thought of as a fixed-cost whose return depends on the scale, which creates an increasing return to scale, known as the *cost-spreading* effect (Cohen and Klepper, 1996a). In short, cost-spreading and business-stealing mechanisms respectively describe the positive and negative effects of the market share of large firms on R&D-return. The paper shows that the combination of these two effects creates an inverted-U relationship between R&D-return and share of large firms. This in turn implies the inverted-U relationship between productivity growth and share of large firms.

Finally, the paper calibrates the parameters to match the aggregate moments of the U.S. economy, and runs two counterfactual exercises for the long- and medium-run. In the long-run exercise, the paper quantifies the effect of the rise in the market share of large firms on productivity growth. A key observation is that the fixed operating-cost of large firms regulates their size. One interpretation of an increase in the fixed operating-cost is that it has grown because of mergers and acquisitions, that in turn was caused by a gradual relaxation of the anti-trust laws since the mid-eighties (Peltzman, 2014). In the long-run exercise, the paper finds the time path of the fixed operating-cost for the period 1985-2017, such that if it is announced at 1985, the endogenous time path of the market share of large firms matches its trend in the data. As the market share of large firms follows its trend in the data, the technology growth rate first increases until the late-nineties, and then declines for the rest of the period. The total loss in productivity growth from the highest point of the inverted-U profile in the late nineties to the current time is about 28 basis points. Comparison of this result to the micro-data evidence suggests a good match between the two. The model also predicts that if the current upward trend in the market share of large firms continues unchanged for another decade, there will be an additional 28 basis-points decline in productivity growth. To put it in perspective, the household would give up about 10 percent of its lifetime consumption to avoid this loss in productivity growth. Thus, the model suggests that rise in the market share of large firms is an important trend that policy makers should be aware of. Particularly, policies that can ease up entry are helpful.

The second counterfactual exercise investigates the response of the model to a negative transitory unexpected supply shock. The paper compares two economies with different levels of the market share of large firms, and shows that there is a larger drop and slower recovery in the number of large and small firms in the more concentrated economy. The intuition is that through the endogenous markup mechanism, as the market share of large firms increases, their profits' response to an exogenous market-size shock gets amplified. This in turn amplifies the return to entry, and causes a larger exit rate in the medium-run. Using a dynamic stochastic general equilibrium (DSGE) framework Ferraro et al. (2017) provide detailed analysis of long- and medium-run effects of corporate tax policies in a similar class of models.

This paper mostly contributes to the endogenous growth literature, pioneered by Romer (1990), and extended to the Schumpeterian *creative destruction* models by Aghion and Howitt (1990) and Grossman and Helpman (1991a), and Schumpeterian *creative accumulation* models by Thompson and Waldo (1994); Smulders and Van de Klundert (1995); Peretto (1996, 1998), and Dinopoulos and Thompson (1998). In the creative accumulation theory, the source of productivity growth is the technological progress of the incumbent firms through process innovation (R&D investment), and recent empirical studies (Bergek et al., 2013; Garcia-Macia et al., 2016) show that in agreement with the premise of the Schumpeterian creative accumulation theory, "most growth appears to come from incumbents", "through improvements of existing varieties rather than creation of new varieties".

The primary theoretical contribution of this paper to the Schumpeterian growth literature is a tractable introduction of heterogeneous firms (large versus small), and showing the existence of the time-invariant inverted-U relationship between productivity growth and the market share of large firms. In contrast, when there exists only one type of firm (*e.g.* Smulders and Van de Klundert, 1995; Peretto, 1996, and subsequent models of this class) R&D-intensity is a decreasing function of the number of firms for any number of firms larger than two, which is clearly not suitable for quantitative exercises. The secondary theoretical contribution of the paper to the literature is that the model has no scale effects in spite of having endogenous markups. It is well known in this literature that if firms internalize their effect on the aggregate price index, the model suffers from scale effects, *i.e.* the growth rate depends on the size of the economy (Peretto and Smulders, 2002). To the best of my knowledge, every growth model with endogenous markup in the literature suffers from the scale effects. In contrast, the paper shows that if only the large firms internalize their effect on the industry price index, it is possible to perfectly sterilized the scale effect. It is done by letting the number of industries absorb the scale of the economy: as the population (size) increases, the number of industries increase such that the steady-state growth rate remains the same for every industry. In spirit, this mechanism is similar to Peretto (1998), and Laincz and Peretto (2006). The technique of introduction of a second state variable to sterilize the scale effect has also been used in Dinopoulos and Thompson (1998); Young (1998); Howitt (1999).

There exists a large empirical IO literature on testing the Schumpeterian hypothesis: that there is a positive relationship between concentration and R&D (Cohen and Levin, 1989; Cohen, 2010). Perhaps the most notable Schumpeterian growth paper that suggested an inverted-U relationship between R&D-intensity and a measure of competition is Aghion et al. (2005). They model each industry with a duopoly, and show that it is possible to have an inverted-U relationship in the aggregate. They also present empirical evidence on the existence of an inverted-U relation between the level of research output (measured by the citation weighted number of patents) and the industry average Lerner-index. Besides having a different mechanism, the paper's empirical exercise furthers the seminal paper of Aghion et al. (2005) in three ways. First, by using R&D-intensity (R&D divided by sales), the paper controls for the size of industries. This is important because the most robust finding of the empirical literature on innovation is that R&D increases with size (Cohen and Klepper, 1996a,b; Cohen, 2010). Also, using the recent U.S. datasets allows the paper to control for the industry fixed effects at a much finer level: *i.e.*, the paper uses four- and six-digit NAICS (North American Industry Classification System), both for the fixed effects and cluster-robustness of the standard errors. Second, the simplicity of the model allows for an easy link between the model parameters and the aggregate moments of the U.S. data. Thus, it is easy to compare the model's predictions with reduced form panel-data regressions. This is a valuable exercise that is absent in most of other Schumpeterian growth papers. Finally, the paper models the product innovation as well as the process innovation, that allows to account for the fluctuations of the number of large and small firms in medium-cycles (Comin and Gertler, 2006). This is desirable since it allows for additional tests on deeper mechanisms at work in the model. For instance, the model predicts that at economic downturns the share of large firms in their own industries increases, that is in agreement with the data.

There exists a growing literature that uses knowledge-based growth models to study macroeconomic fluctuations in medium-cycles. The pioneer paper of this literature is Comin and Gertler (2006) and some of the recent related contributions are Bianchi et al. (2014), Corhay et al. (2015), Kung and Schmid (2015), Anzoategui et al. (2016) and Ferraro et al. (2017). This paper contributes to this literature by identifying the mechanism through which the market share of large firms affects the impulse response of the macroeconomic variables to an unexpected transitory negative supply shock. The paper shows that in an economy with more concentrated industries, as the negative shock hits the economy, the number of large firms (or equivalently the number of industries) decreases, but the market share of large firms within industries increases. The intuition is that due to the knowledge spillover effect, a smaller number of industries means a lower measure of public technology available to small firms, which lowers small firms' productivity more that the large firms, and makes small firms lose their market share to large firms. This implies that to the right of the inverted-U curve between R&D-intensity and the market share of large firms, a negative transitory supply shock further lowers the R&D incentive of large firms and leads to a slower recovery. This paper simulates a negative transitory supply shock to two economies with different levels of the market share of large firms and shows that the response of the number of firms is much deeper and its recovery is much slower for the more concentrated economy.

In general, this paper contributes to the macroeconomic literature that features endogenous market structure (Etro, 2009). Particularly, the paper contributes to the design of models with endogenous markup and entry (Jaimovich and Floetotto, 2008; Bilbiie et al., 2012) by focusing on the marked difference between the markup of large versus small firms, the former being countercyclical while the latter being acyclical. This helps with the understanding of why it is hard to empirically identify markup cyclicality if the market share is not accounted for (Nekarda and Ramey, 2013). Moreover, the paper identifies a new propagation mechanism: when large firms engage in more process innovation, a negative supply shock has a lower impact on product innovation, and hence on large firms' entry. Thus, propagation of shocks through entry depends on the large firms' process innovation, which in turn depends on their market share. This also contributes to the macroeconomic literature that studies the business-cycle effects of slowdown in firm creation (Clementi et al., 2014; Pugsley and Sahin, 2015; Clementi and Palazzo, 2016). Additionally, the paper shows that if a negative shock is strong enough to cause R&D investment to shut down (an occasionally binding constraint), then the convergence dynamic changes and the speed of convergence reduces, causing a further slowdown in the recovery of the number of firms. This is in contrast to papers that do not account for the effect of endogenous markup in profitability (Ferraro and Peretto, 2014).

The rest of the paper is organized as follows: section 2 presents the empirical results. Section 3 goes over the model and its analytical solution. Section 4 describes the general equilibrium and stability analysis of the solution. Section 5 discusses parameter identification and calibration. Section 6 presents the quantitative results of the counterfactual exercises, and section 7 concludes. All proofs are relegated to the appendix.

2.2 Empirical Evidence

This section shows that at the aggregate level there exists a clear upward trend in the employment share of large firms (ESOLF) and the market share of large firms (MSOLF), and then presents the industry panel data empirical results: first, there is an inverted-U relationship between R&D-intensity and the ESOLF in research-based industries. Second, the ESOLF is a perfect proxy for the MSOLF, and hence the previous result naturally extends to the MSOLF as well. The section concludes with a brief interpretation of the results.

Typical measures of competition in the literature are the Herfindahl-Hirschman index (HHI) and the Lerner index (LI). However, it is hard to measure the HHI consistently across industries and in the aggregate, and in order to measure the LI one has to estimate cost and profit for firms, which is prone to measurement error especially for private firms. This is important because these measures change very slowly over time and measurement error can substantially impede identification of their trend. To address these issues, the paper defines the following two measures: 1) employment share of large firms (ESOLF), that is, employment in large firms divided by total employment; 2) market share of large firms (MSOLF), that is, sales of large firms divided by total sales. These measures can be easily applied to individual industries or to the whole economy, and can be measured accurately, which is essential in the identification of slow long-run trends.

To define large and small operationally, the paper looks at the size distribution of employment across all publicly traded firms over time. The annual median employment size, averaged over time for the past three decades gives a number around 600 employees. There exist few national panel of industry databases that have the number of firms disaggregated by employment size. The paper uses the Business Dynamic Statistics (BDS) and the Statistics of U.S. Businesses (SUSB), and the smallest size bin that contains larger-than-the-median public firms is the one that starts from 500 employees. Hence, the definition of a large firm is fixed to be a firm that has more than 500 employees, but the results are qualitatively robust to this number.

With these definitions in hand, the paper focuses on the trend in the share of large firms over the past three decades, depicted in figure 2.2. It shows a slow but consistent rise in the share of large firms since the mid eighties. For comparison, the figure shows that whether a large firm is defined as having more that 500 employees, or just having more than 20 employees, the pattern is the same. The figure serves two purposes: first, it shows that the share of large firms (ESOLF and MSOLF) was on the rise, and the pattern is very robust to the definition of large. Second, because the total change in the left and right axes are close, it shows that large firms grew at the expense of (very) small firms with less that 20 employees that do not have market power. This is important because a key mechanism of this paper hinges on the large firms' expansion at the expense of small firms.

The key ingredient of the model is the inverted-U relationship between R&D-intensity and the market share of large firms. The paper validates this relationship empirically using a panel of U.S. industries, and shows that it is robust to different specifications. Think of the relation $y_t = f(s_t)$, where y_t and s_t represent the R&D-intensity and ESOLF. Log-linearization up to second order gives:

$$\log(y_t) \approx \beta_0 + \beta_1 \log(s_t) + \beta_2 \big(\log(s_t)\big)^2.$$

Thus, an inverted-U relationship is equivalent to $\beta_1 > 0$ and $\beta_2 < 0$ in the following regression:

$$\begin{aligned} \log(\text{R\&D-intensity}_{i,t} + 1) = \beta_0 + \beta_1 \log(\text{ESOLF}_{i,t} + 1) + \beta_2 \log(\text{ESOLF}_{i,t} + 1)^2 \\ + \beta X_{i,t} + \alpha_i + \epsilon_{i,t}, \qquad (2.1) \end{aligned}$$

where α_i represents the industry fixed-effect, and other controls are in the term βX.

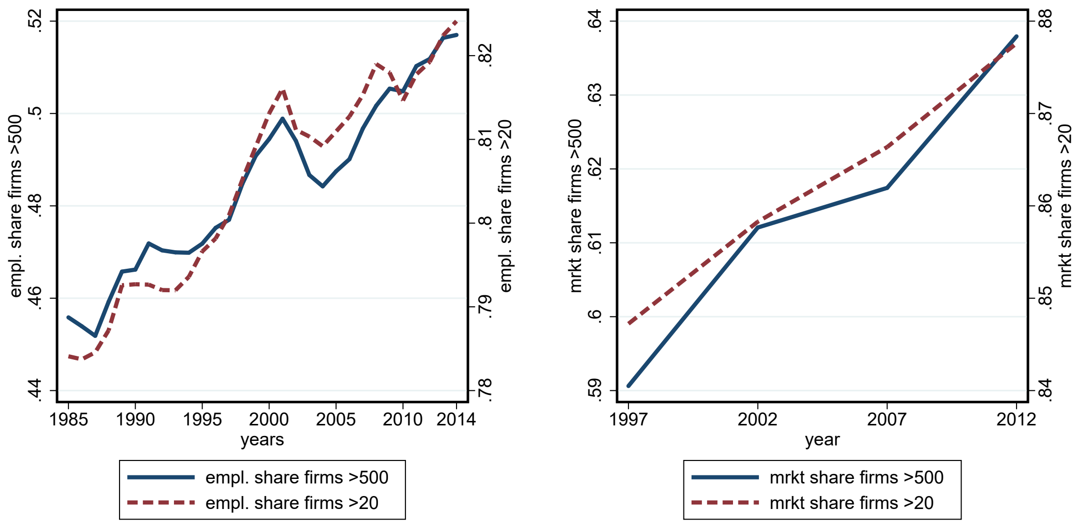

FIGURE 2.1: Employment/market share of large firms.

Left panel shows the employment share of the large firms (ESOLF) in the economy using the BDS data. Right panel shows the market share of large firms (MSOLF) in the economy using the SUSB data. In both panels, the left vertical axis is the share of firms larger than 500 employees, and the right vertical axis is the share of firms larger than 20 employees. The graph shows an upward trend in the employment/market share of large firms.

Figure 2.2 (left panel) shows the scatter plot of log(R&D-intensity+1) versus log(ESOLF+1), where both R&D-intensity and ESOLF are measured in basis points (*i.e.*, they range between zero and ten-thousands). The paper constructs R&D-intensity using the Compustat-CRSP-Merged (CCM) data of public firms (a proxy for large firms). For each industry-year, R&D-intensity is the sum of all R&D investment by public firms in that industry, divided by their sales, times 10,000 (so that the changes are measured in basis-points). The paper constructs ESOLF using the SUSB data, and for each industry-year it is the employment in large firms divided by the total employment in that industry, times 10,000. The sample of the graph is the top 60 research-based industries, defined as industries with the highest R&D investment relative to their size. To select the top research-based industries (at 4-digit NAICS), the paper constructs the time-aggregated R&D divided by the time-aggregated sales for all the 4-digit NAICS industries over the duration of the data (1998-2014), and picks the top 60 industries. Two 4-digit NAICS industries with only one firm for all years are dropped from the sample, since their data is much more volatile compared to the rest of industries (the median number of firms in the research-based industries is 15, and the mean is 37). But it should be noted that the results are robust to the inclusion/exclusion of one-firm industries, and to the cutoff number 60, as the robustness checks show later on. Each point in figure 2.2 (left panel) shows an industry-year, and a brief inspection reveals that there exists an inverted-U relation between the R&D-intensity and the employment share of large firms (ESOLF). The plot also depicts the predicted values for the regression of log(R&D-intensity) on {log(ESOLF+1), log(ESOLF+1)^2} with industry and year fixed effects, along with their 95% cluster-robust confidence intervals.

The fixed effect regression in the left panel of figure 2.2 suggests that as the ESOLF increases, industries with smaller ESOLF increase their R&D-intensity, while industries with high ESOLF reduce their R&D-intensity. The right panel of figure 2.2 shows the top 10 research-based industries with the highest increase in ESOLF during the decade 2002-2012. Each arrow shows the starting time and the ending time positions of an industry. A quick inspection reveals that the industries seem to move along the inverted-U relation drawn in the left panel of figure 2.2.

Table A.1 reports the coefficients of the above inverted-U relationship between R&D-intensity and the ESOLF, with the standard errors reported in parenthesis. All regressions control for the year and industry fixed-effects, and the standard errors in parentheses are cluster-robust for each industry. The regressions also control for the time-lag of sales growth rate: $(sale_{i,t-1} - sale_{i,t-2})/sale_{i,t-2}$, because the past empirical studies showed the importance of accounting for the growth condition of industries (Ali et al., 2008). The coefficient of sales growth is significant in all specifications, but it is very small and the results are robust to its exclusion. The first

$$\log(\mathrm{rdI}_{i,t} + 1) = \beta_0 + \beta_1 \log(\mathrm{ESOLF}_{i,t} + 1) + \beta_2 \log(\mathrm{ESOLF}_{i,t} + 1)^2 + \alpha_i + u_{i,t}$$

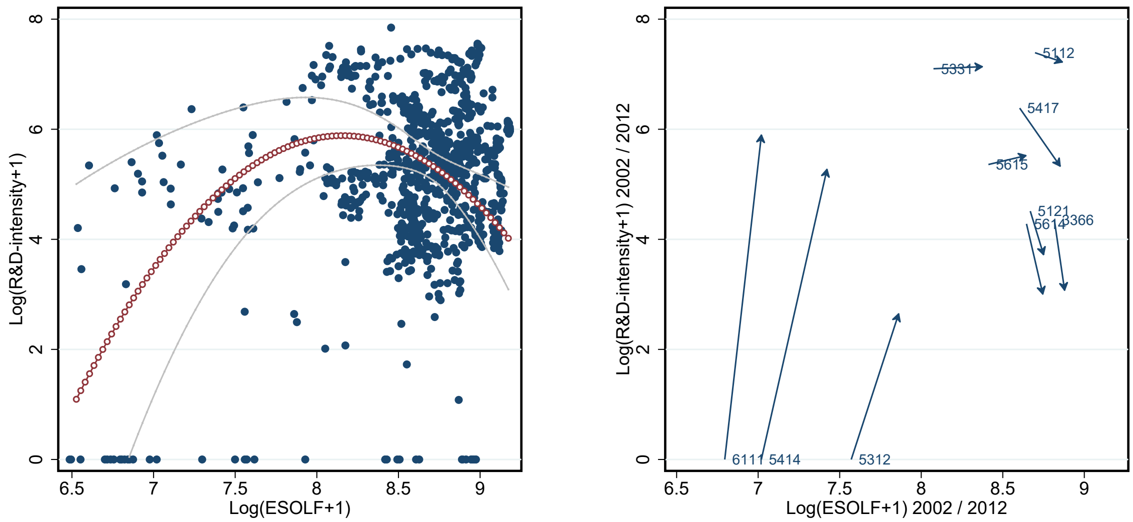

Figure 2.2: Inverted-U relation between R&D-intensity and share of large firms.

The left panel's scatter plot shows the log of R&D-intensity versus the log of ESOLF, both measured in basis points. Each dot is an industry-year for the top-60 industries at 4-digit-NAICS in years 1998-2014. The red circle curve shows the predicted values for the regression with year and industry fixed effects, and the gray solid curves show the industry cluster-robust 95% confidence intervals. The right panel shows the top ten research-based industries with the largest increase in the ESOLF during the decade (2002-2012). Source: Industry R&D-intensity is constructed using the CCM data, and ESOLF is constructed using the SUSB data, for the sample of top 60 research-based industries.

column includes the top 90 6-digit NAICS research-based industries. Other columns show that the results are robust to the number of industries that are included in the sample. Figure A.1 summarizes the coefficients β_1 and β_2 above, along with their 90% confidence interval as the sample size of top research-based industries are increased by 5 at a time. Figure A.1 shows that the coefficients are significant when the number of top research-based industries pass 60, and until it reaches 245, at which point more than 99.5% of all R&D investment by public firms is accounted for, as can be seen in figure A.2. Moreover, the results remain robust to using 4-digit NAICS instead of 6-digit NAICS.

Next, the paper shows that the pattern is quite robust to the inclusion/exclusion of controls. Table A.2 shows the estimation results for the top 60 research-based industries at 4-digit NAICS. In particular, table A.2 shows that the coefficients are very significant and do not vary much with the inclusion/exclusion of industry and year effects. Also, the standard errors only mildly increase after cluster-robustness. Notice that the last column in table A.2 is the specification that is used in figure 2.2.

It is important to address the potential endogeneity problem of ESOLF, that in the empirical literature is usually referred to as the 'reverse causality' problem (Sutton, 1991). Since R&D-intensity and ESOLF are jointly determined in a system of equations, in order to tease out the effect of ESOLF on R&D-intensity one needs an instrument variable (IV) that affects R&D-intensity, only through ESOLF. Similar to Aghion et al. (2005), the paper uses a regulation index as IV. Specifically, the paper uses the panel of regulation index provided by Al-Ubaydli and McLaughlin (2017), called RegData, together with two industry control variables (lag of industry employment and number of public firms) to instrument for the ESOLF. Since RegData only exist for 4-digit NAICS, the IV exercises are limited to 4-d NAICS. Table A.3 reports the result: the first column is the usual fixed-effect regression with IVs included as regressors. The second column is the two stage least square (2SLS) regression, and the third column is the limited information maximum likelihood (LIML) estimation. The fixed effect OLS (first column) shows that in the presence of my original regressors, IVs are not significant, and do not change other coefficients compared to the previous regression in table A.2. The 2SLS regression shows that both β_1 and β_2 coefficients are almost ten times larger when we allow the instruments to tease out their effect. The first-stage regressions' statistics are reported in table A.4. In the first-stage, the year and industry fixed effect are controlled for and the standard errors are cluster-robust (just like the second stage). The first column shows the F-statistics for the joint significance of the instruments together with their p-values. The second column shows the Sanderson-Windmeijer (SW) χ^2 tests for the under-identification of the instruments, based on Sanderson and Windmeijer (2016). As the p-values show, the null of under-identification is rejected at 5%. The last column shows the SW F-tests for the weak identification of instruments. The p-values of the SW F-tests show that the null of weak identification can be rejected at 10%. In order to check the robustness of the coefficients to weak-identification, the third column of table A.3 shows the results of the LIML estimation, which is more robust to weak-identification. It shows that the coefficients grow marginally larger and the significance levels have not changed.

As a final robustness check, the paper repeats the exercise in table A.1, but using the 4-digit NAICS and the 2SLS method, the same as the second column of table A.3. The results are reported in table A.5, and a similar pattern emerges: the coefficients are significant and robust to the changes in the number of the top 4-digit research-based industries that I include in the sample.

So far the paper documents two empirical facts: 1) share of large firms at the aggregate level, measured by aggregate ESOLF and MSOLF, has been increasing over the past three decades; 2) there is an industry-level inverted-U relationship between R&D-intensity and the ESOLF. Since it is more convenient to write the theoretical model in terms of the market share of large firms (MSOLF), the last piece of empirical evidence is to show that ESOLF is a perfect proxy for MSOLF, both at the industry-level and aggregate. For the industry level, figure A.3 shows the scatter plot of ESOLF vs MSOLF for all the years of available data on MSOLF, *i.e.* 2002, 2007, 2012. Each point is an industry-year, constructed using the SUSB data. The left panel shows all the data at 6-digit NAICS, and the right panel shows the data at 4-digit NAICS. The correlation between ESOLF and MSOLF for both panels is about 95%. At the aggregate level, figure A.4 shows ESOLF vs MSOLF. Each point is for the U.S. data, but since the aggregate MSOLF for 1997 is available in SUSB, the graph has 4 data points, and the correlation between ESOLF and

MSOLF is about 1. This shows that one can use the aggregate ESOLF data to approximate the total rise in the MSOLF since the mid eighties. Notice that the left panel of figure 2.2 shows that there was about 4.7% increase in the MSOLF in 15 years (1997-2012). With a constant time-trend in ESOLF, it is easy to estimate that MSOLF must have increased by about twice as much, *i.e.*, about 9.5% in the past three decades. In the appendix, the paper shows that the model predicts a linear relation between ESOLF and MSOLF, that is strongly supported by the data.

Interpreting the results: the paper uses columns (1) and (2) of table A.3 as baseline for interpretation. Given the regression equation (2.1), the maximum R&D-intensity happens at:

$$\text{ESOLF}^{*} = \exp(-\frac{\beta_1}{2\beta_2}).$$

Substituting the coefficients from columns (1) and (2) gives: $\exp(\frac{23.3}{2*1.38}) \approx \%46$, and $\exp(\frac{237}{2*14.1}) \approx \%45$ respectively. Next, recall that the aggregate ESOLF has increased by about 6.0% during the past three decades: starting at about 46% around 1985, and ending at about 52% around 2014 (see figure 2.2). Also, the elasticity of R&D-intensity with respect to ESOLF is: $\beta_1 + 2\beta_2 \log(\text{ESOLF})$, where both R&D-intensity and ESOLF are in units of basis points. Substituting the coefficients in columns (1) and (2) of table A.3 shows that at 6.0% above the maximum ESOLF the elasticity is -0.34 and -3.6 respectively. Moreover, the total predicted decline in R&D-intensity is 2.1% and 25%, which can have a modest to large effect on productivity growth. To quantify the effect of a drop in R&D-intensity on productivity growth the paper develops a Schumpeterian endogenous growth model in the next section, and then uses the calibrated model for counterfactual exercises.

2.3 Model

The production side of the economy consists of a competitive final good producer that buys intermediate products as its input. In each industry there are two types of intermediate products: the *brand*, and its imperfect substitute *generic* product. The final good producer combines the brand and its generic version using a CES technology.

Each brand is produced by a "dominant firm" with a large market share. Dominant firms and large firms are the same in the model. The generic product is produced by many atomistic small firms that constitute the competitive fringe for the large firm. The large firm has market power and sets its own price. In contrast, the competitive fringe are price takers. There is a continuous measure n of industries in the model, and each industry contains a dominant firm and its competitive fringe.

There are two types of innovation: *process innovation*, that is undertaken by large firms in order to lower the marginal cost of production (same as R&D), and *product innovation*, that is undertaken by entrepreneurs and is the source of creation of new large firms (same as entrepreneurship). Of course each type of innovation needs investment.

Finally, there is a standard household that makes the consumption and saving decision. There is no physical capital in the model, and the household inelastically provides the labor needed in all the production processes. In the following subsections, each part of the model is discussed in detail.

2.3.1 Final Good Producer

The final good producer buys the brand and generic products from every industry and combines them into the final good and sells it competitively. The final good is denoted by $\mathscr{X}$, and the brand and generic products of industry i are denoted by X_i

and X_{0i} respectively. The technology of the final good producer is the following:

$$\ln \mathscr{X} = \frac{1}{n}\int_0^n \ln \mathscr{X}_i \, di, \quad \mathscr{X}_i = \left(X_i^{\frac{\epsilon-1}{\epsilon}} + X_{0i}^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}}, \quad \epsilon > 1, \tag{2.2}$$

where n is the measure of industries. The paper denotes the price of the final good by $\mathscr{P}$, and $\mathscr{P}_i$ is the price of $\mathscr{X}_i$ that is the industry i's combined good.

The final good sector induces the following demand schedule for the industry i's output:

$$\mathscr{X}_i = \left(\frac{\mathscr{P}\mathscr{X}}{n}\right)\frac{1}{\mathscr{P}_i}. \tag{2.3}$$

It is easier to rewrite the above equation in terms of *expenditures* on the final good and the industry i's output, denoted by $\mathscr{Y}$ and $\mathscr{Y}_i$ respectively:

$$\mathscr{Y}_i = \frac{\mathscr{Y}}{n}, \quad \text{with} \quad \mathscr{Y}_i \equiv \mathscr{P}_i\mathscr{X}_i, \quad \text{and} \quad \mathscr{Y} \equiv \mathscr{P}\mathscr{X}. \tag{2.4}$$

The induced demand for the brand product and its generic counterpart in industry i are listed below:

$$X_i = \left(\frac{P_i}{\mathscr{P}_i}\right)^{-\epsilon}\mathscr{X}_i, \quad \text{and} \quad X_{0i} = \left(\frac{P_{0i}}{\mathscr{P}_i}\right)^{-\epsilon}\mathscr{X}_i, \tag{2.5}$$

where P_i and P_{0i} are the price of X_i and X_{0i} respectively. Hence, the demand for X_i and X_{0i} in terms of their price, and total industry expenditure and its price index are the following:

$$X_i = \frac{\mathscr{Y}_i P_i^{-\epsilon}}{\mathscr{P}_i^{1-\epsilon}}, \quad \text{and} \quad X_{0i} = \frac{\mathscr{Y}_i P_{0i}^{-\epsilon}}{\mathscr{P}_i^{1-\epsilon}}. \tag{2.6}$$

The competitiveness of the final good producer implies the industry price index:

$$\mathscr{P}_i^{1-\epsilon} = P_i^{1-\epsilon} + P_{0i}^{1-\epsilon}. \tag{2.7}$$

The market share of a large firm in its own industry s_i is an important state variable of the model, that is calculated below:

$$s_i = \frac{P_i X_i}{\mathscr{P}_i\mathscr{X}_i} = \frac{P_i\left(\frac{P_i}{\mathscr{P}_i}\right)^{-\epsilon}\mathscr{X}_i}{\mathscr{P}_i\mathscr{X}_i} = \frac{P_i^{1-\epsilon}}{\mathscr{P}_i^{1-\epsilon}}. \tag{2.8}$$

Notice that s_i is the model counterpart of the MSOLF (market share of large firms) in the previous sections.

2.3.2 Intermediate Good Industries

The brand producer and its competitive fringe are detailed in this sections. The section concludes with a discussion on the choice of market structure.

Dominant (Large) Firms

Each dominant firm i has a private technology denoted by Z_i, that determines its productivity. The dominant firm can invest and increase its Z_i. This reduces its marginal cost of production and is formally known as *process innovation.* There is also a fixed operating cost for a large firm, denoted by ϕ. The dominant firm has to hire labor for the production and also for the process innovation, denoted respectively by L_{X_i} and L_{Z_i}. The following equation shows the dominant firm's production technology:

$$X_i = Z_i(L_{X_i} - \phi). \tag{2.9}$$

The technology of process innovation is summarized by:

$$\dot{Z}_i = \alpha \overline{Z} L_{Z_i}, \tag{2.10}$$

where $\overline{Z}$ denotes the public knowledge in the economy and is defined by:

$$\overline{Z} = \frac{\int_{j \in n} Z_j \, dj}{L}, \tag{2.11}$$

and L is the total labor force. $\overline{Z}$ is a measure of aggregate technology, and notice that knowledge (technology) spillover from each process innovator to the public knowledge is embedded in its specification. In particular, each dominant firm does not take it into account that its innovation makes future innovations easier for everyone. This specification resembles Peretto and Connolly (2007), but it is not the same. The appendix provides a micro-foundation of this technology based on learning-by-doing in the process innovation.

Optimal Decision: Each dominant firm takes the demand of the final good producer, and chooses its price and technology investment to maximize its market valuation, *i.e.* net present value of its future dividends. The value of the dominant firm in industry i, denoted by V_i, is the following:

$$V_i = \int_t^{\infty} e^{-\int_t^{\tau}(r(s)+\delta)\, ds} D_i(\tau)\, d\tau,$$

where r is the interest rate, δ is the exogenous probability of obsolescence (equivalent to the large firms' death rate), and D_i is the dividend. The cost of the dominant firm is the wages payed to labors whom are employed either in production or in R&D, and are denoted by L_{X_i} and L_{Z_i} respectively. Thus, the dominant firm's dividend flow is the following:

$$D_i = P_i X_i - W\left(L_{X_i} + L_{Z_i}\right).$$

Using the production technology to replace for L_{X_i}, and then using the final good producer's demand to replace for X_i, one can rewrite the dividend as:

$$D_i = \mathscr{Y}_i \frac{P_i^{1-\epsilon}}{\mathscr{P}_i^{1-\epsilon}} - \frac{W}{Z_i} \mathscr{Y}_i \frac{P_i^{-\epsilon}}{\mathscr{P}_i^{1-\epsilon}} - W\phi - W L_{Z_i}.$$

Now one can use the investment technology to construct the current value Hamiltonian:

$$\mathscr{H}^c = \mathscr{Y}_i \frac{P_i^{1-\epsilon}}{\mathscr{P}_i^{1-\epsilon}} - \frac{W}{Z_i} \mathscr{Y}_i \frac{P_i^{-\epsilon}}{\mathscr{P}_i^{1-\epsilon}} - W\phi - W L_{Z_i} + \lambda(\alpha \overline{Z} L_{Z_i}).$$

The first order conditions associated to this Hamiltonian are listed below:

$$\frac{\partial \mathscr{H}^c}{\partial P_i} = 0$$

$$\frac{\partial \mathscr{H}^c}{\partial L_{Z_i}} = 0$$

$$(r+\delta)\lambda = \dot{\lambda} + \frac{\partial \mathscr{H}^c}{\partial Z_i}.$$

The solution to the optimal pricing problem is the following endogenous markup price:

$$P_i = \frac{\xi_i}{\xi_i - 1} MC_i, \text{ where } \xi_i = \epsilon - (\epsilon - 1)s_i, \ MC_i = \frac{W}{Z_i}, \text{ and } s_i = \frac{P_i^{1-\epsilon}}{\mathscr{P}_i^{1-\epsilon}}. \tag{2.12}$$

The intertemporal solution to the optimal investment problem is:

$$W = \lambda\alpha\overline{Z}$$

$$(r+\delta)\lambda = \dot{\lambda} + \frac{W}{Z_i^2}\mathscr{Y}_i\frac{P_i^{-\epsilon}}{\mathscr{P}_i^{1-\epsilon}} = \dot{\lambda} + \frac{1}{Z_i}\frac{W}{Z_i}\frac{1}{P_i}\mathscr{Y}_i\frac{P_i^{1-\epsilon}}{\mathscr{P}_i^{1-\epsilon}} = \dot{\lambda} + \frac{1}{Z_i}\frac{\xi_i - 1}{\xi_i}\mathscr{Y}_i s_i.$$

Using the first equation to substitute for λ in the second equation gives the following Euler equation for technology investment (*i.e.* process innovation):

$$r + \delta = \frac{\dot{W}}{W} - \frac{\dot{\overline{Z}}}{\overline{Z}} + \frac{\alpha\overline{Z}}{WZ_i}\mathscr{Y}_i s_i \frac{\xi_i - 1}{\xi_i}. \tag{2.13}$$

Competitive Fringe

In each industry there is a measure of small (atomistic) competitive firms that produce a homogeneous generic product, that is an incomplete substitute for the monopolist's brand product. Since the firms in competitive fringe make no profit, they cannot invest in their technology. Thus, they cannot have access to private process innovation. However, small firms have access to the public knowledge $\overline{Z}$, defined in equation (2.11). Hence, labor productivity in small firms depends on this aggregate technology. The intuition is that each industry is contributing a particular technology to the technology pool. Thus, a larger measure of industries means that small firms will have a larger accessible pool of technology, which makes it is easier for small firms to produce.

A fixed marginal cost of production depending on aggregate technology is equivalent to the linear production function below:

$$X_{0i} = \beta\overline{Z}L_{X_{0i}}. \tag{2.14}$$

Competitive fringe make no profit, and their price equals their marginal cost of production. Thus, the price of the competitively produced generic goods is

$$P_{0i} = MC_{0i} = \frac{W}{\beta \bar{Z}}. \tag{2.15}$$

Note that the number of small firms in the competitive fringe is not important because of the linearity of the production function and the homogeneity of the generic good. These firms make no profit, pay no dividend, and it is free to set up a small (or atomistic) firm in the competitive fringe. Of course the total production share of the competitive fringe in the industry $(1 - s_i)$ plays a role when it comes to investment decision of the large firms as we saw in the previous section.

2.3.3 Discussion of Market Structure

In order to have a concrete example of the market structure, one can think of a pharmaceutical industry where there is a brand drug with a significant market share whose producer is a dominant firm with a high market power. However, there are many generic drugs that are imperfect substitutes for the brand. But since generic drugs are being produced competitively, there is no market power for their producers. As another example, consider detergent products in chemical industry, where there is a well known Proctor and Gamble brand, but many retailer also sell their own cheaper substitute products.

The industry structure of a dominant firm with a competitive fringe proposed above is a good fit for any oligopolistic industry where there is a degree of coordination among its dominant players. The pattern of "*price leadership* in lieu of overt *collusion*" has been first recognized in the influential work of Markham (1951). He presents price leadership as a "monopolistic solution to the oligopolists' pricing coordination problem". According to him, "collusive price leadership is most likely to emerge when (a) the industry is tightly oligopolistic, (b) seller's products are close substitutes, (c) cost curves are similar, (d) there are barriers to entry of new rivals, and (d) demand for industry's output is relatively inelastic." Scherer and Ross (1990) further explain that collusive price leadership is often juxtaposed with its weaker version: the notion barometric leadership. They provide an in-depth analysis of a range of industries including cigarettes, steel, automobiles, cereals, turbogenerators and even gasoline and conclude that although there is no clear line drawn between the strong and weak concepts of price leadership, nevertheless one can observe a good degree of coordination in all these industries. As an example, General Electric's industry price leadership worked even better than outright collusion in the period before its conviction of price fixing (Lean et al., 1985). As another example, Yoffie (2011) presents the case of "Cola wars" between Coke and Pepsi and shows that they more than often emulate each other, including in price changes. The result of the "Cola wars" between 1970 and 2010 is that their combined market share rose from less than 55% to above 70%, at the expense of many smaller competitors. To see other examples together with a theory of price leadership see Rotemberg and Saloner (1990). Altogether, the evidence suggests that a model of a monopolist with a competitive fringe can be representative of the U.S. industries at least for the later part of the 20th century where almost all industries have been operating as tight oligopolies with few large dominant firms, together with some small firms without market power. Lastly, the CCM data shows that at the level of 6-digit NAICS, and among manufacturing industries that contain at least one public firm (proxy for large firm), about fifty percent of industries contain only two public firms. This lends additional support to this paper's choice of industry structure.

2.3.4 Entrepreneurs

Entrepreneurs can incur a fixed cost and invent a new product, which in the literature is referred to as the product innovation (Abernathy and Utterback, 1978). This starts a new industry that immediately gets populated with small firms and the entrepreneur is the dominant firm. The paper assumes that the initial cost of kick starting a new industry depends linearly on the size of the industry, measured by the consumer expenditure:

$$V_i = \gamma \mathscr{Y}_i. \tag{2.16}$$

This cost can be paid by any labor who deems it profitable to become an entrepreneur. Note that since there is no physical capital in the model and labor is the only production factor in the economy, this cost can be thought of as the entrepreneur hiring labor (including himself) to create the new firm.

The no arbitrage condition for the value of a firm is the following well known equation

$$r + \delta = \frac{D_i + \dot{V}_i}{V_i},$$

and since entrepreneurship activity is free entry, one can replace the firm value with the above cost of creation to arrive at

$$r + \delta = \left(\mathscr{Y}_i s_i \frac{1}{\xi_i} - W\phi - W \frac{\dot{Z}_i}{\alpha \overline{\overline{Z}}} \right) \frac{1}{\gamma \mathscr{Y}_i} + \frac{\dot{\mathscr{Y}}_i}{\mathscr{Y}_i}. \tag{2.17}$$

Notice that the derivation has used the optimal price equation (2.12), and the investment technology (2.10) to substitute for $P_i X_i - W L_{X_i}$ and L_{Z_i} respectively.

2.3.5 Household

There is a household who makes the consumption and saving decision. For tractability, the household's utility is assumed logarithmic: $U(C) = \log(C)$, where C is the current real consumption. Thus, the household's problem can be written as

$$\max \int_t^\infty \mathrm{e}^{-\rho(\tau - t)} \log(C_\tau)\, d\tau$$

$$\text{s.t. } \dot{Q} = rQ + \psi W L - \mathscr{P} C, \quad \forall \tau \geqslant t \tag{2.18}$$

where Q denotes household's financial wealth. Parameter ψ shows how much of the wage income the household has access to, namely spendable income. For example, the household has to work the portion $1-\psi$ of his time for the government, and this effort is not productive. Since labor is the only factor of production, and all technologies are linear in labor, an unexpected change in ψ acts as an exogenous shock to total factor productivity, or simply a supply shock. Thus, in general, ψ must be understood as time variant: $\psi = \psi(t)$.

The paper denotes the consumption expenditure $\mathscr{P}C$ by $\tilde{\mathscr{Y}}$, and one can use it to find the household's well known first order condition:

$$\frac{\dot{\tilde{\mathscr{Y}}}}{\tilde{\mathscr{Y}}} = r - \rho. \tag{2.19}$$

So far, the paper has derived the partial equilibrium solution for each block of the model: final good producer, dominant firms and their competitive fringe, entrepreneurs, and the household. The next section finds the general equilibrium of the model, and discusses its transitional dynamics.

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This cost can be paid by any labor who deems it profitable to become an entrepreneur. Note that since there is no physical capital in the model and labor is the only production factor in the economy, this cost can be thought of as the entrepreneur hiring labor (including himself) to create the new firm.

The no arbitrage condition for the value of a firm is the following well known equation

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and since entrepreneurship activity is free entry, one can replace the firm value with the above cost of creation to arrive at

$$r + \delta = \left(\mathscr{Y}_i s_i \frac{1}{\xi_i} - W\phi - W\frac{\dot{Z}_i}{\alpha \overline{Z}}\right)\frac{1}{\gamma \mathscr{Y}_i} + \frac{\dot{\mathscr{Y}}_i}{\mathscr{Y}_i}. \tag{2.21}$$

Notice that the derivation has used the optimal price equation (2.12), and the investment technology (2.10) to substitute for $P_i X_i - W L_{X_i}$ and L_{Z_i} respectively.

2.3.8 Household

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$$\text{s.t. } \dot{Q} = rQ + \psi WL - \mathscr{P}C, \quad \forall \tau \geqslant t \tag{2.22}$$

where Q denotes household's financial wealth. Parameter ψ shows how much of the wage income the household has access to, namely spendable income. For example, the household has to work the portion $1-\psi$ of his time for the government, and this effort is not productive. Since labor is the only factor of production, and all technologies are linear in labor, an unexpected change in ψ acts as an exogenous shock to total factor productivity, or simply a supply shock. Thus, in general, ψ must be understood as time variant: $\psi = \psi(t)$.

The paper denotes the consumption expenditure $\mathscr{P}C$ by $\tilde{\mathscr{Y}}$, and one can use it to find the household's well known first order condition:

$$\frac{\dot{\tilde{\mathscr{Y}}}}{\tilde{\mathscr{Y}}} = r - \rho. \tag{2.23}$$

So far, the paper has derived the partial equilibrium solution for each block of the model: final good producer, dominant firms and their competitive fringe, entrepreneurs, and the household. The next section finds the general equilibrium of the model, and discusses its transitional dynamics.

2.4 General Equilibrium

The general equilibrium of the model is the set of allocations $\mathscr{X}$, C, L_n, $\{X_i, X_{0i}\}_{i\in n}$, $\{L_{X_i}, L_{Z_i}, L_{X_{0i}}\}_{i\in n}$, and prices $\mathscr{P}$, $\{P_i, P_{0i}, V_i\}_{i\in n}$, r such that given the state variable n, $\{Z_i\}_{i\in n}$, ψ, the allocations and prices solve the partial equilibrium problem of the final good producer, dominant firms and their competitive fringe, entrepreneurs, and the household. Finally, product and labor markets clear: $\mathscr{X} = C$ (or equivalently

$\mathscr{Y} = \tilde{\mathscr{Y}}$), and $\psi L = \int_{i \in n} (L_{X_i} + L_{Z_i} + L_{X_{0i}})\, di + L_n$, where L_n is the total labor hired by entrepreneurs.

This paper focuses on the symmetric equilibrium where all industries are identical. Note that by construction, equation (2.2) implies that the final good producer spends the same amount on each industry. Thus, in order to have a symmetric equilibrium it is enough to have the same level of technology Z_i and market share s_i in all industries, *i.e.* $Z_i \equiv Z$, $s_i \equiv s$. Similarly, the paper drops the identifier i from the rest of the allocations and prices in the definition of general equilibrium above. Also, for the indexed calligraphic letters we have $\mathscr{Y}_i = \frac{\mathscr{Y}}{n}$ and $\mathscr{P}_i = \mathscr{P} n$. The technology growth rate is denoted by $z \equiv \frac{\dot{Z}}{Z}$.

To find the solution to the symmetric dynamic general equilibrium, the paper replaces $\tilde{\mathscr{Y}} = \mathscr{Y}$ in equation (2.23), and uses it in the household's budget constraint (3.3) to replace for the interest rate r:

$$\dot{Q} = \left(\frac{\dot{\mathscr{Y}}}{\mathscr{Y}} + \rho\right) Q + \psi W L - \mathscr{Y}.$$

Q is the value of all firms in the economy. However, small firms worth nothing since they pay no dividend (they have no capital, and there is free entry). Thus, Q is the value of all monopolist firms in the economy: $Q = nV$. But recall from equation (2.20) that $V = \gamma \frac{\mathscr{Y}}{n}$ and hence we have $Q = \gamma \mathscr{Y}$. Dividing the above equation by Q and replacing for $Q = \gamma \mathscr{Y}$ gives

$$\frac{\dot{\mathscr{Y}}}{\mathscr{Y}} = \left(\frac{\dot{\mathscr{Y}}}{\mathscr{Y}} + \rho\right) + \frac{\psi W L - \mathscr{Y}}{\gamma \mathscr{Y}}.$$

This is solved for $\mathscr{Y}$:

$$\mathscr{Y} = \frac{\psi W L}{1 - \rho\gamma}. \tag{2.24}$$

Replacing the above value of $\mathscr{Y}$ in (2.23) gives the equilibrium interest rate:

$$r = \rho + \frac{\dot{\psi}}{\psi} + \frac{\dot{W}}{W}. \tag{2.25}$$

The paper still has not chosen the numeraire, and it is easy to see that normalizing the wage reduces the dynamic dimension of the system. Thus, henceforth we have $W = 1$.

The paper imposes the symmetric equilibrium conditions on the dominant firms' optimal technology investment condition (2.13) to arrive at

$$r + \delta = -\frac{\dot{n}}{n} - z + \alpha \frac{\mathscr{Y}}{L} s \frac{\xi - 1}{\xi},$$

and then uses equations (2.24) and (2.25) to replace for $\mathscr{Y}$ and r to arrive at

$$\rho + \delta = -\frac{\dot{\psi}}{\psi} - \frac{\dot{n}}{n} - z + \frac{\alpha \psi}{1 - \rho\gamma} s \frac{\xi - 1}{\xi}, \text{ where } z \geqslant 0. \tag{2.26}$$

The reason for $z \geqslant 0$ is that firms' R&D employment L_Z must be nonnegative.

In general equilibrium, the market share of large firms s depends only on the number of industries n. To see the relation between s and n, use equation (2.8) and replace the prices:

$$s_i = \frac{P_i^{1-\epsilon}}{P_i^{1-\epsilon} + P_{0i}^{1-\epsilon}} = \frac{1}{1 + \left(\frac{P_i}{P_{0i}}\right)^{\epsilon - 1}} = \frac{1}{1 + \left(\frac{\xi_i}{\xi_i - 1} \frac{MC_i}{MC_{0i}}\right)^{\epsilon - 1}} = \frac{1}{1 + \left(\frac{\xi_i}{\xi_i - 1} \frac{1}{Z_i} \beta \frac{\int_{j \in n} Z_j \, dj}{L}\right)^{\epsilon - 1}},$$

and now imposing the symmetric equilibrium conditions simplifies this expression to

$$s = \frac{1}{1 + \left(\frac{\xi}{\xi - 1} \frac{\beta n}{L}\right)^{\epsilon - 1}}. \tag{2.27}$$

Recall that $\xi = \epsilon - (\epsilon - 1)s$, and hence equation (2.27) can be solved for $n(s)$ as the following:

$$n(s) = L \frac{\epsilon - 1}{\beta} \left(\frac{1 - s}{s}\right)^{\frac{1}{\epsilon - 1}} \frac{1 - s}{\epsilon - (\epsilon - 1)s}. \tag{2.28}$$

It is easy to show that $n(s)$ is strictly decreasing in s, and hence there is a bijection between the share of large firms s in their own industry, and the number of large firms n.

Lemma 1. *The measure of industries n is strictly decreasing in the market share of large firms s: that is $s'(n) < 0$.*

Proof. See the appendix. $\square$

Thus, equation (2.26) implies that the growth rate of technology at the firm level is only a function of the dynamics of measure of share of large firms $s$industries, and the exogenous force ψ.

Finally, the paper rewrites the entrepreneurs' optimal product innovation condition (2.21) with $\mathscr{Y}$ and r replaced by (2.24) and (2.25):

$$\rho + \frac{\dot{\psi}}{\psi} + \delta = \Big(\frac{\psi L}{(1-\rho\gamma)n} s \frac{1}{\xi} - \phi - \frac{zL}{\alpha n}\Big) \frac{n(1-\rho\gamma)}{\gamma\psi L} + \frac{\dot{\psi}}{\psi} - \frac{\dot{n}}{n}.$$

The paper then uses (2.26) to replace for z. After simplification and accounting for the corner solutions we have:

$$\begin{cases} \epsilon_{n,s}(s)\frac{\dot{s}}{s}\left(1 - \frac{1-\rho\gamma}{\alpha\psi\gamma}\right) = \frac{s}{\gamma}\frac{2-\xi}{\xi} - \rho - \delta - \frac{\phi n(1-\rho\gamma)}{\gamma\psi L} + \frac{1-\rho\gamma}{\alpha\psi\gamma}\left(\frac{\dot{\psi}}{\psi} + \rho + \delta\right) & \text{if } L_Z > 0 \\ \epsilon_{n,s}(s)\frac{\dot{s}}{s} = \frac{s}{\gamma}\frac{1}{\xi} - \rho - \delta - \frac{\phi n(1-\rho\gamma)}{\gamma\psi L} & \text{if } L_Z = 0 \\ \epsilon_{n,s}(s)\frac{\dot{s}}{s} = -\delta & \text{if } L_N = 0 \end{cases} \tag{2.29}$$

where $\epsilon_{n,s}(s) = \frac{s}{n}\frac{dn}{ds}$ is the elasticity of number of large firms to their market share. Notice that this expression is completely in terms of the endogenous variable s and its functions $n(s)$, and $\xi(s)$, and the exogenous law of motion of ψ, which can be thought of as our forcing process. This completes the solution of the model: knowing the state variable s, and the law of motion of ψ is enough to know the dynamics of s and hence $n(s)$. Knowing s and $n(s)$, together with equation (2.26) gives us z. The rest of the endogenous variables are easily obtained from their equations. For instance, equations (2.24) and (2.25) give us:

$$\mathscr{Y} = \frac{\psi L}{1-\rho\gamma}, \quad \text{and} \quad r = \rho + \frac{\dot{\psi}}{\psi}.$$

Equations (2.12) and (2.15) give the dominant firms' prices and that of their competitive fringes given the state variable Z:

$$P = \frac{\xi}{\xi - 1}\frac{1}{AZ}, \quad \text{and} \quad P_0 = \frac{1}{\beta A \frac{n}{L} Z},$$

using which we can deduce the allocations X and X_0 from equation (2.6) as the following:

$$X = \frac{1}{P}\frac{\mathcal{Y}}{n}s, \quad \text{and} \quad X_0 = \frac{1}{P_0}\frac{\mathcal{Y}}{n}(1 - s).$$

Labor allocations $\{L_X, L_Z, L_{X_0}\}$ come from (2.9), (2.10), and (2.14) respectively, and using (2.20) we have $V = \gamma\frac{\mathcal{Y}}{n}$.

In section 2.4.1 the paper derives the conditions under which the solution to the differential equation (2.29) is stable, and after calibration it becomes clear that the sufficient conditions are easily satisfied. As a result, on the balanced growth path s settles in its steady-state value that is the solution to the right hand side of (2.29).

2.4.1 Stability Analysis

The previous section showed that dynamics of the whole model boils down to the dynamics of the measure of industries n (or equivalently the market share of large firms s). Thus, it is crucial to characterize the conditions under which the supply and demand of new firms create a stable equilibrium on the balanced growth path (BGP).

Product Innovation: Demand and supply

This section derives the expressions for the total value of demand and supply of large firms as a function of the number of large firms n. The paper shows that there is a sufficient condition that guarantees the demand function to be decreasing on the BGP. Because the supply function is constant in n, the paper concludes that the partial equilibrium solution for product innovation has a stable solution.

The demand for large firms is the value that a buyer would pay for a share of the firm given its dividend yield and capital gains. This is summarized by the no arbitrage condition below

$$r + \delta = \frac{D + \dot{V}}{V},$$

where the industry subscript i is dropped in the symmetric equilibrium. First, the paper uses the fact that on the BGP $\mathscr{Y}$ is constant (see equation 2.24), and thus V does not grow. This means that on the BGP we have $\dot{V} = 0$. Second, the paper uses (2.25) and the fact that $W \equiv 1$, and $\psi = 1$ to deduce that on the BGP we have $r = \rho$, and thus I can write

$$V^d = \frac{1}{\rho + \delta} D.$$

To write the above expression in terms of the measure of industries n, the paper simplifies the expression for $D = PX - L_X - L_Z$:

$$\begin{aligned} D &= \frac{\mathscr{Y}}{n} \frac{P^{1-\epsilon}}{\mathscr{P}^{1-\epsilon}} - \frac{1}{Z} X - \phi - \frac{z}{\alpha(\frac{n}{L})} \\ &= \frac{\mathscr{Y}}{n} s - \frac{1}{ZP} PX - \phi - \frac{1}{\alpha(\frac{n}{L})} \Big(-\rho - \delta + \frac{\alpha \mathscr{Y}}{L} s \frac{\xi - 1}{\xi} \Big) \\ &= \frac{\mathscr{Y}}{n} s - \frac{\xi - 1}{\xi} \frac{\mathscr{Y}}{n} s - \phi + \frac{\rho + \delta}{\alpha(\frac{n}{L})} - \frac{\mathscr{Y}}{n} s \frac{\xi - 1}{\xi} \\ &= \frac{1}{(1 - \rho\gamma)(\frac{n}{L})} s \frac{2 - \xi}{\xi} - \phi + \frac{\rho + \delta}{\alpha(\frac{n}{L})}. \end{aligned}$$

Hence, the total demanded value of monopolist firms as a function of n is the following:

$$nV^d = \frac{1}{\rho + \delta} \Big[\frac{L}{(1 - \rho\gamma)} s \frac{2 - \xi}{\xi} - n\phi + \frac{(\rho + \delta)L}{\alpha} \Big]. \tag{2.30}$$

The supply function is the total cost of making large firms (or equivalently kick starting new industries) as a function of the measure of industries n. Recall that the cost of kick starting a new industry depends linearly on the size of that industry, namely $V_i = \gamma \mathscr{Y}_i$, which in a symmetric equilibrium becomes $V^s = \gamma \frac{\mathscr{Y}}{n}$. Hence, the supply function on the BGP is

$$nV^s = \frac{\gamma L}{1 - \rho\gamma}, \tag{2.31}$$

showing that the total supply function is constant. The intuition is that in a symmetric equilibrium a larger number of industries means each industry must be smaller, and hence it costs less to create it.

Notice that as long as the demand function in (2.30) is decreasing in the measure of firms n, the equilibrium is stable. Since the coefficient of n in (2.30) is negative, and the only other function of n in the expression is s, it remains to check if the function $s^{\frac{2-\xi}{\xi}}$ is decreasing in n. But recall from lemma 1 that $n(s)$ is a decreasing function. I show that the function $s^{\frac{2-\xi}{\xi}}$ in increasing in s if the parameter ϵ is not too large. Intuitively, it means that the generic product of the competitive fringe must not be a close substitute for the brand. Of course in practice, it is subjective to define the boundary of an industry, and hence what can be considered a generic product for a brand is within the scope of the researcher's decision. Moreover, as the reader sees later in the calibration section, the calibrated value of ϵ is inside the sufficient condition's range.

Lemma 2. *The function $s^{\frac{2-\xi}{\xi}}$ is increasing in s if a generic product is somewhat substitutable for the brand, meaning the value of ϵ is not too large. In particular, it is true for any value of $\epsilon \in (1, 2]$.*

Proof. See the appendix. $\square$

Thus, lemmas 1 and 2 together show that the total value demanded for large firms is decreasing in n. I formally state this in the following proposition:

Proposition 3. *The demand for dominant firms is decreasing in the number of dominant firms n if ϵ is not too large.*

Proof. See the appendix. □

Notice that $\epsilon \in (1, 2]$ is just a sufficient condition. Even when it is violated, the function $s\frac{2-\xi}{\xi}$ becomes increasing only for values of s close to one which is far above the average value of s in the data. On top of that, even if the function $s\frac{2-\xi}{\xi}$ becomes increasing in n, it is not necessarily enough to swamp $-n\phi$ in equation (2.30) unless s is sufficiently close to one.

Assuming our condition for a decreasing demand is satisfied, the constant supply means that the solution to n is stable. For instance, if the economy is on the BGP and suddenly some firms unexpectedly die, the demand for monopolist firms exceeds its supply meaning it becomes profitable for entrepreneurs to innovate more products and the measure of large firms (or industries) goes back to its long-run equilibrium value.

Product vs Process Innovation

Differential equation (2.29) dictates the dynamics of n, and in order for it to have a stable solution, we need the slope of $\frac{\dot{n}}{n}$ as a function of n be negative where it intersect with the horizontal axes.

It is clear from the proof of proposition 3 that the function $s\frac{2-\xi}{\xi}$ is decreasing in n for ϵ not too large. Thus, when the solution product innovation is stable, the solution to the differential equation in (2.29) is stable if and only if the coefficient of $\frac{\dot{n}}{n}$ on the left hand side is positive. Hence, the condition for the stability of the equilibrium around BGP can be summarized in the following proposition.

Proposition 4. *Suppose that demand for product innovation is decreasing (ϵ not too large). Then, the model has a stable solution if and only if it is not too cheap to* *create a new dominant firm (γ not too small).*

Proof. See the appendix. □

Henceforth, the paper assumes that the conditions ϵ not too large and γ not too small are met such that the solution to (2.29) is stable.

2.4.2 Transitional Dynamics

The previous section showed that the steady-state value of the market share of large firms is stable. This section focuses on the phase diagram of the model, *i.e.*, the graph of $\dot{s}$ versus s. This is important because it shows us the qualitative behavior of the system when it is not close to its steady-state: for example, when the number of large firms is lower than its steady-state value n_{ss}, product innovation goes up and process innovation goes down. But it is possible that the number of large firms drops too low, such that the R&D investment is totally shut down. The paper shows that this causes a drop in the speed of convergence to the steady-state, compared to the hypothetical case where the R&D could go negative. One interpretation is that at the aggregate level, the resources that goes to process innovation creates a buffer from which the resources that goes to product innovation is (partially) taken at bad times. When the buffer is dried out (*i.e.* R&D investment is zero), the only option is to take from the resources that goes to production, but this is harder because its adverse effect on consumption is felt right away. Thus, the rate of convergence to steady-state depends heavily on the state of the economy as we will see in this section.

Imposing no external forces (*i.e.*, no unexpected shocks) simplifies the Euler equation of R&D investment (2.26) to the following:

$$z(s;\psi) = \begin{cases} -(\rho+\delta) - \left(\frac{\dot{\psi}}{\psi} + \epsilon_{n,s}(s)\frac{\dot{s}}{s}\right) + \frac{\alpha\psi}{1-\rho\gamma} s \frac{\epsilon-(\epsilon-1)s-1}{\epsilon-(\epsilon-1)s} & \text{if } L_Z > 0 \\ 0 & \text{otherwise,} \end{cases}$$

where $\epsilon_{n,s}(s) = \frac{s}{n}\frac{dn}{ds}$ is the elasticity of number of large firms to their market share. Recall that substituting this equation into the Euler equation of product innovation yields the differential equation (2.29) for the dynamics of the share of large firms s below:

$$\epsilon_{n,s}(s)\frac{\dot{s}}{s} = \begin{cases} \left[1 - \frac{1-\rho\gamma}{\alpha\psi\gamma}\right]^{-1}\left[\frac{s}{\gamma}\frac{2-\xi}{\xi} - \rho - \delta - \frac{\phi n(1-\rho\gamma)}{\gamma\psi L} + \frac{1-\rho\gamma}{\alpha\psi\gamma}\left(\frac{\dot{\psi}}{\psi} + \rho + \delta\right)\right] & \text{if } L_Z > 0 \\ \frac{s}{\gamma}\frac{1}{\xi} - \rho - \delta - \frac{\phi n(1-\rho\gamma)}{\gamma\psi L} & \text{if } L_Z = 0 \\ -\delta & \text{if } L_N = 0. \end{cases}$$

It is easy to understand the transitional dynamics of the system by characterizing the critical values at which process- or product-innovation starts (or shuts down). The next proposition provides this characterization.

Proposition 5. *Given a range of parameters, there exist unique points s_e and $s_{\underline{z}} < s_{\overline{z}}$ such that:*

$$L_N > 0 \Leftrightarrow s > s_e$$

$$L_Z > 0 \Leftrightarrow s \in (s_{\underline{z}}, s_{\overline{z}}).$$

Moreover, if the solution is stable and the parameter of the cost of product innovation is not too large, then we have $s_{\underline{z}} < s_e < s_{\overline{z}}$.

Proof. See the appendix. □

The intuition is that when the share of dominant firms is too small, their markup is too low and thus they are not very profitable. Hence, it is not viable for entrepreneurs to incur the initial fixed cost and engage in product innovation. In this case the dominant firms exit until their market share grows large enough that it becomes viable for entrepreneurs to pay the entry cost. The critical point at which product innovation begins is named s_e, after which the return to entry should equal r in the general equilibrium. Similarly, when the share of dominant firms is too small, the return to process innovation doesn't justify R&D-investment. However, there is a point $s_{\underline{z}}$ at which the market share of dominant firms becomes large enough that R&D-investment is turned on. But if the market share of large firms grows too large, namely larger than $s_{\overline{z}}$, the business-stealing effect lowers the return to entry so much that the R&D-investment shuts down again.

Plain Transitional Dynamics (No External Forces)

In order to better understand the transitional dynamics, it is instructive to discuss the phase diagram under no shocks. The system under no shocks is presented below:

$$\begin{cases} \rho + \delta & \geqslant -z + \frac{\alpha}{1-\rho\gamma} s \frac{\epsilon-(\epsilon-1)s-1}{\epsilon-(\epsilon-1)s} - \epsilon_{n,s}\frac{\dot{s}}{s} \\ \rho + \delta & \geqslant \left[\frac{1}{1-\rho\gamma} \frac{s}{n(s)} \frac{1}{\epsilon-(\epsilon-1)s} - \phi - \frac{z}{\alpha n(s)} \right] \frac{1-\rho\gamma}{\gamma n(s)} - \epsilon_{n,s}\frac{\dot{s}}{s}. \end{cases} \tag{2.32}$$

Note that $z(s)$ is zero outside the interval $(s_{\underline{z}}, s_{\overline{z}})$, and the maximum z can be below, at, or above the s_e. The first configuration where the maximum z is below the s_e is shown in the graph 2.3. The top panel shows the phase diagram of $\dot{s}$ versus s, whose slope gives us the rate of change in s. Notice that the crossing point where $\dot{s}$ intersects with the horizontal line is the steady-state. The fact that $\dot{s}$ goes from positive to negative values shows that the steady-state is stable. Starting from the left of the diagram where $s < s_{\underline{z}}$, there is no entry and only exit. This lowers the number of large firms, while increasing the market share of the remaining ones. As the market share of large firms surpasses the $s_{\underline{z}}$, the incumbents start investing in their technology, but there is still no firm entry and the remaining incumbents are getting larger. After the market share of large firms grows enough to surpass the s_e, the product innovation begins. Of course product innovation lowers the net exit rate, and as the phase diagram shows, the market share of large firms starts converging

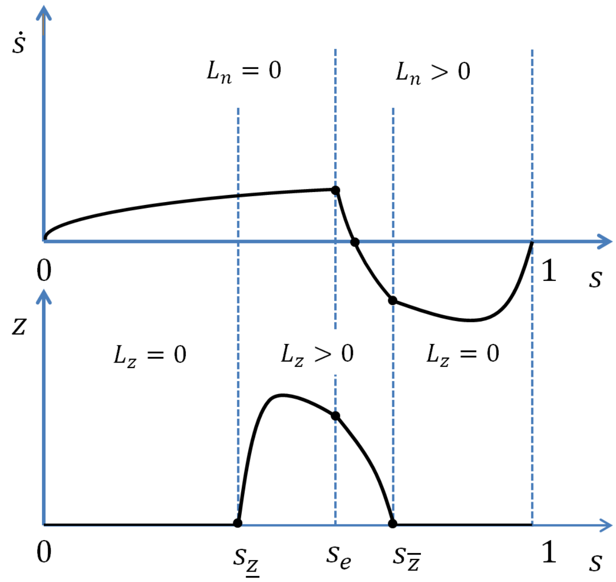

FIGURE 2.3: Phase diagram (the first configuration, absent the shocks).

to its steady-state. At the right of the steady-state, there is a point $s_{\overline{z}}$ at which the R&D investment by the incumbents shut down due to the fact that it is becoming prohibitively costly to increase the market share via R&D investment.

It is also important to discuss the speed of convergence when the R&D-investment is turned on and off (at $s_{\overline{z}}$) because of its ramification for large recessions, when the R&D-investment hits its zero lower bound. This is not restrictive and the results can be extended to smaller recessions: for instance, in an extension of the model with heterogeneous industries, even small shocks can send a some of large firms into the region where R&D-investment hits the zero lower bound. Particularly, the paper shows that as the R&D-investment is turned on, the rate of convergence increases, *i.e.*, the slope of $\dot{s}$ versus s is more negative (locally) at the left of the point $s_{\overline{z}}$ compared to its right.

Proposition 6. *The rate of product innovation increases when the process innovation is turned on.*

Proof. See the appendix. □

The intuition behind the proposition 6 is the following. Notice that in equilibrium the return to entry is constant. Now if the entry rate increases, *i.e.*, the $\frac{\dot{n}}{n}$ goes up, it reduces the return to entry because the capital gains drops (since the value of firms drops). But for the return to entry to remain constant in equilibrium, an increase in $\frac{\dot{n}}{n}$ must be accompanied with a decrease in n such that the profit of firms increases, and the increase in their dividend-yield counterbalances the reduction in the capital gains. Next, suppose that the R&D-investment is activated, which means that it must have the same constant return as the return to entry. However, an increase in $\frac{\dot{n}}{n}$ also reduces the return to R&D-investment. But it means that smaller investment in R&D generates the same desired growth rate in technology, which marginally increases the dividend-yield. Of course this means that a smaller counterbalancing change in n is needed for the return to entry to remain constant. This implies that for n larger than $n_{\overline{z}}$ (associated with $s_{\overline{z}}$) the $\frac{\dot{n}}{n}$ versus n must be steeper. This in turn means that for $s < s_{\overline{z}}$ the $\frac{\dot{s}}{s}$ must have a more negative slope.

It is easy to see that $z(s)$ is time invariant. Note that when $z > 0$ and there is entry, both inequalities in (2.32) bind. Replacing $\epsilon_{n,s}\frac{\dot{s}}{s}$ from one equation into the other, and solving for productivity growth z gives an inverted-U shape that is time invariant. Also, when there is no product innovation and $\epsilon_{n,s}\frac{\dot{s}}{s} = -\delta$, the productivity growth equals

$$z(s) = -\rho + \frac{\alpha}{1-\rho\gamma} s \frac{\epsilon - (\epsilon - 1)s - 1}{\epsilon - (\epsilon - 1)s},$$

which is a time invariant inverted-U again.

Figure 2.4 depicts the other two possible configurations where the maximum of the inverted-U happens at the point s_e, and to its right. However, it is possible for the maximum of the above function to be larger or smaller than s_e.

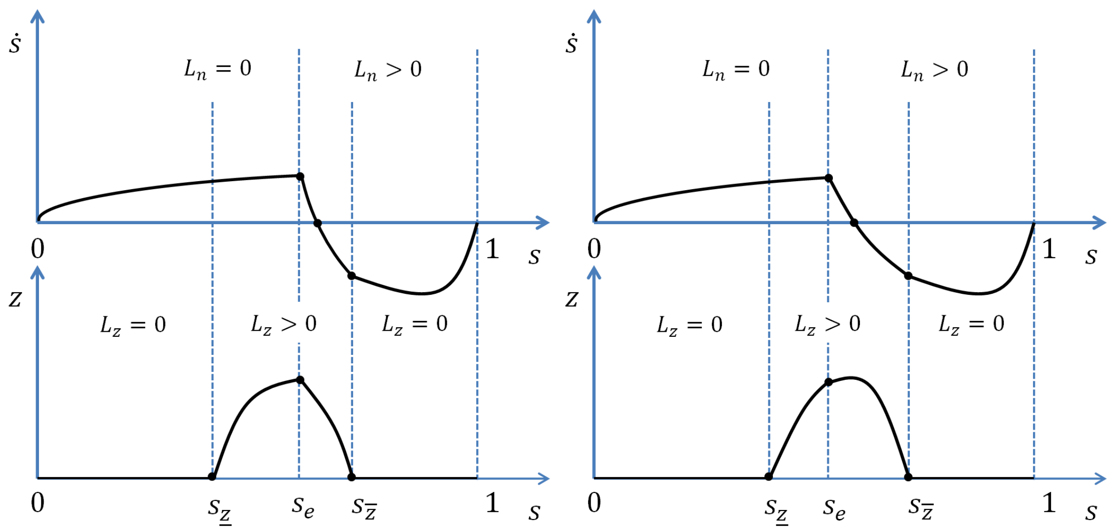

FIGURE 2.4: Phase diagram (other configurations, absent the shocks).

2.4.3 Market Share of Large Firms

In the long run and on the balanced growth path, s settles in its steady-state and hence the measure of large firms $n(s)$ is constant. This shows that there is no extensive margin of growth in the long-run, and hence, growth only depends on the investment of large firms in their technology. In this section the market share of large firms s is the key variable that determines the technology investment, and the relation is *not* monotonic. In order to see this, let us start with the no arbitrage condition in the process-innovation (2.13), in our symmetric general equilibrium:

$$z = -(\rho + \delta) - \frac{\dot{\psi}}{\psi} - \frac{\dot{n}}{n} + \frac{\alpha\psi}{1-\rho\gamma} s \frac{\epsilon - (\epsilon - 1)s - 1}{\epsilon - (\epsilon - 1)s},$$

which on the BGP with a constant ψ reduces to

$$z(s) = -(\rho + \delta) + \frac{\alpha\psi}{1-\rho\gamma} s \frac{\epsilon - (\epsilon - 1)s - 1}{\epsilon - (\epsilon - 1)s}.$$

The growth on the balanced growth path $z(s)$ is plotted in figure 2.5, which shows an inverted-U function. This is due to the combination of two effects: *cost spreading* effect manifested by s, and *business stealing* effect manifested by $\frac{\epsilon-(\epsilon-1)s-1}{\epsilon-(\epsilon-1)s}$. A larger

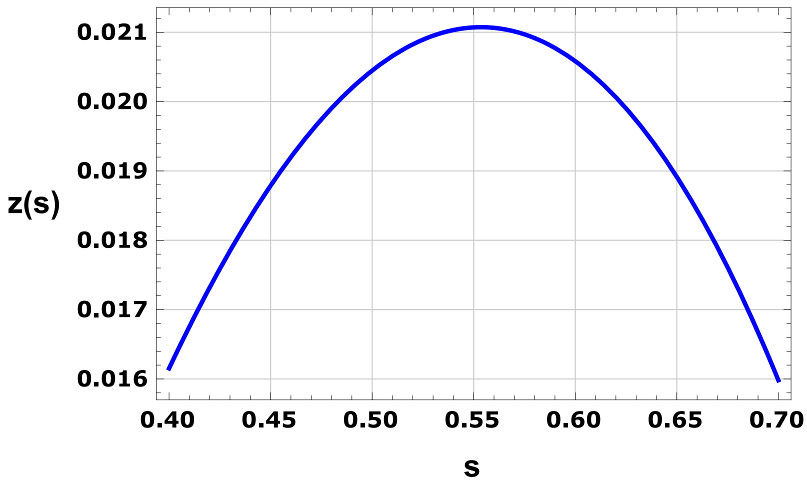

FIGURE 2.5: Graph of $z(s)$ on the balanced growth path.

s means less competition for the dominant firms, and hence the cost-spreading effect is anti-competitive. In contrast, the ratio $\frac{\epsilon-(\epsilon-1)s-1}{\epsilon-(\epsilon-1)s}$ is decreasing in s. Thus, the business stealing effect diminishes as s grows larger and hence it is pro-competitive.

One can see that if the dominant firms do not internalize their effect on the industry price index, then the ratio $\frac{\epsilon-(\epsilon-1)s-1}{\epsilon-(\epsilon-1)s}$ gets replaced by the constant $\frac{\epsilon-1}{\epsilon}$, and the business stealing effect disappears from the $z(s)$ expression. This would yield the classical Schumpeterian conclusion that competition has anti-growth effect on investment and it is all due to the cost spreading effect. The intuition behind the cost spreading effect is that R&D is a fixed cost whose benefit is reduction of the marginal production cost and thus a higher profit for each unit sold. It is as if the cost is being spread over the total production, and the return is larger when more units are being sold. As a result, the larger the market share, the higher the return on investment, which in turn means higher R&D investment, and higher growth.

When the large firms take into account that they can change the industry price index, the markup becomes endogenous and the ratio $\frac{\epsilon-(\epsilon-1)s-1}{\epsilon-(\epsilon-1)s}$ emerges in $z(s)$. This can be interpreted as the large firms business stealing incentive from the competitive fringe. However, the larger the market share, the harder in gets to increase it by R&D investment. In particular, it is impossible to have the whole market. The fact that an increase in the market share reduces the business stealing incentive of the monopolists is the source of its pro-competitive growth effect.

The hump shape of the graph of $z(s)$ indicates that there is a certain level of s such that below this level, the cost spreading effect dominates the business stealing effect. Thus, an increase in s and reduction in competition increases large firms' R&D investment and hence rises the growth rate. On the other hand, when s is larger than that certain level, the business stealing effect dominates and an increase in s suppresses R&D investment and hinders growth.

2.4.4 No Scale Effect

One of the necessary properties of an endogenous growth model is *no scale effect*: that is the growth rate should not depend on the population size. If a model suffers from scale effect, it counterfactually exaggerates the response to any shock that changes the scale or equivalently the market size. Moreover, the issue of calibrating the scale becomes tricky as it can no longer be treated as 'just a scaling constant'. This section shows that the model does not suffer from scale effect. In particular, the scale is fully absorbed in the measure of industries.

Lemma 7. *The measure of industries n on the BGP is linear in scale L. In other words, $\frac{n}{L}$ is a constant that only depends on the parameters of the model.*

Proof. See the appendix. □

Note that (2.29) implies $\frac{n}{L}$ out of equilibrium is a function of the shock and its time path as well. However, lemma 7 shows that on the BGP, $\frac{n}{L}$ depends the parameters of the model except L. Next, the paper uses lemma 7 and shows that the model has no scale effect.

Proposition 8. *No scale effect: The growth rate z is independent of L.*

Proof. See the appendix. □

The intuition of proposition 8 is that as the scale of the economy grows, the measure of industries grow proportionally such that the share of large firms s (which depends only on $\frac{n}{L}$) does not change, and hence all industries grow just as before.

2.4.5 Permanent Shock to Fixed Operating Cost

The fixed operating cost parameter ϕ regulates the size of dominant firms. The larger the fixed operating cost, the large the dominant firm. In the paper, the increase in the size of dominant firms in the past three decades is models by an increase in the fixed operating cost. For instance, mergers and acquisitions can create larger firms with higher fixed operating cost (see section 2.6.1 for details). This section explains the qualitative dynamics of the model in response to a permanent increase in the fixed operating cost. Consider an equilibrium where both product and process innovations are turned on. That is, the equations in system (2.32) hold with equality. Figure 2.6 plots the dynamics in the space of technology growth rate versus market share of large firms. As the fixed operating cost ϕ jumps up unexpectedly, the dividends drop. This means that the return to entry goes down, and hence the there will net exit, which in turn means that the market share of large firms will increase. But this means that the return to process innovation jumps up due to intangible capital appreciation. This is shown in the figure by the vertical jump in the technology growth rate. However, as the market share of large firms grows, the technology growth rate moves down along the new path due to the business-stealing effect. It is easy to show that if we start from the right of the hump, the end point is lower than the starting point.

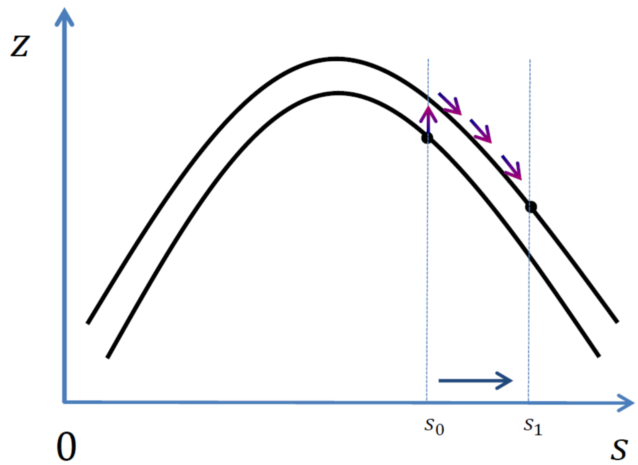

FIGURE 2.6: Technology growth rate $z(s)$ in response to a permanent increase in fixed operating cost ϕ.

2.5 Calibration

The first subsection below discusses the moments that are targeted and the data that are used to calculate the moments. The second subsection shows the identification of the parameters given the targeted moments.

2.5.1 Data and targeted moments

The major emphasis of the model is on the distinction between the large dominant firms and small competitive firms, and hence the first task is to define and quantify large versus small firms. Based on the U.S. census BDS data, firms of size 1-4 employees make up more than 55% all firms, and thus the median of firm size distribution is less than 5. Using the same data, the average firm size is 21.6. Both of these numbers show how skewed the firm size distribution is. If we think of a representative large firm as one that is large enough to be publicly traded, we can acquire the relevant firm size information by looking at the median size of all public firms using the CCM database. If we look at the median size of public firms at each year, it shows an upward trend, and it is just above 500 around the year 2000. Moreover, the time average of this statistics between 1985-2007 is 644 employees. Since we want to look at the employment and market share of the large firms in the census data, and the above statistics fall in the bin-size ‘firms larger than 500 employees’, then the paper defines ‘large’ as a firm with 500 employees. An important benefit of taking the public firms as a proxy for large firms is that later in this section, we can also use the CCM data to find the average dividend-yield for large firms.

The paper uses the BDS data and finds the time-average exit rate of establishments of size 500-999 to directly calibrate the death rate parameter δ. This yields the calibrated death rate of $\delta = 5.7\%$. Data shows that the death rate of large firms is stable, *i.e.*, it has no trend and no large fluctuations (Tian, 2015), and thus firms’ death rate parameter δ is a good moment to target.

The paper targets the per capita output growth rate and the risk-free rate. The time average of per capita output growth rate after the postwar until the great recession is 2.0%. To calibrate the risk-free rate the paper uses the CRSP treasury and inflation indexes to calculate the difference in the time average of one year coupon bond return minus the CPI. This gives the time-averaged (ex-post) real risk free rate, which is 3.0% in the period after the great moderation and before the great recession 1985-2007.

The long-run growth in the model is driven by the large firms’ R&D-investment. Hence, it is essential that we target a measure of aggregate R&D-intensity. A particularly informative ratio is that of R&D to GDP. Using the NIPA series of R&D and GDP, the paper constructs the R&D-to-GDP ratio and take its average over time in the great moderation era, that yields 2.5%.

In order to calibrate the parameter γ, the paper uses the equation $V_i = \gamma \mathscr{Y}_i$. Note that $\mathscr{Y} = n\mathscr{Y}_i$ is the total consumption expenditure, and nV_i is the total asset holding of the household because small firms are competitive and their dividend (and hence their value) is zero. Moreover, one can rewrite the above equation as

$$\gamma = \frac{V_i}{\mathscr{Y}_i} = \frac{\frac{nD_i}{n\mathscr{Y}_i}}{\frac{nD_i}{nV_i}} = \frac{\text{dividend consumption ratio}}{\text{dividend price ratio}}.$$

In order to compute the dividend consumption ratio, the paper uses the NIPA series B056RC1 and DPCERC1. In order to compute the dividend price ratio, the paper uses the CRSP series VWRETD and VWRETX for value weighted returns including and excluding dividends respectively. The dividend price ratio is

$$\frac{\text{dividend}}{\text{price}} = \frac{\text{VWRETD} - \text{VWRETX}}{1 + \text{VWRETX}}.$$

Using the above series and time averaging the ratio for the period after the great moderation era, the paper finds that $\gamma = 2.8$.

In order to calculate the market share of large firms (MSOLF), the paper uses the SUSB data on total receipts disaggregated by firm-sizes, that contains four data points at years: 1997, 2002, 2007, and 2012. Given that around the year 2000 the median size of large firms was about 500, the paper looks at the market share of large firms at year 2000. A simple interpolation reveals that the market share of large firms at the year 2000 was about 60%. Hence, the paper targets the MSOLF (at 2000) to be $s = 0.60$.

2.5.2 Identification

The set of parameters in the model are $\{\rho, \delta, \gamma, \alpha, \beta, \epsilon, \phi\}$. From the previous section, large firms' death rate is calibrated at $\delta = 5.7\%$ using the DBS data. Also, the ratio (dividend/consumption)/dividend-yield that was found from the NIPA and CRSP data gave a calibration for $\gamma = 2.8$. Risk-free rate is calibrated using the CRSP data at 3.0%, that is $r = 0.03$. Using equation (2.25) at the BGP gives $r = \rho$, and hence $\rho = 0.03$.

In order to identify α, the paper uses the R&D-to-GDP ratio which is calibrated at 2.5%. Using the entry cost (2.20), total expenditure (2.24), and the fact that GDP on the balanced growth path is $WL + nD$, one can write

$$GDP = WL + nD = 1 + (\rho + \delta)\gamma\mathscr{Y} = 1 + \frac{\gamma(\rho + \delta)}{1 - \rho\gamma}.$$

Thus, the R&D-to-GDP ratio is

$$\frac{\text{R\&D}}{\text{GDP}} = \frac{nL_Z}{1 + \frac{\gamma(\rho+\delta)}{1-\rho\gamma}}.$$

But using equation (2.10), we have $L_z = \frac{z}{\alpha\frac{n}{L}}$, Thus, one can write

$$\frac{\text{R\&D}}{\text{GDP}} = \frac{z}{\alpha}\frac{1}{1 + \frac{\gamma(\rho+\delta)}{1-\rho\gamma}}, \tag{2.33}$$

and the per capita GDP growth rate is calibrated at 2.0%, that is $z = 0.02$. Hence, equation (2.33) can be solved for α, that gives $\alpha = 0.632$.

To identify ϵ the paper starts with equation (2.26) for large firms' technology investment on BGP, and substitute for $\xi = \epsilon - (\epsilon - 1)s$.

$$\rho + \delta = -z + \frac{\alpha}{1 - \rho\gamma}s\frac{\epsilon - (\epsilon - 1)s - 1}{\epsilon - (\epsilon - 1)s}.$$

Since α is already identified in (2.33), and s is targeted at 60%, the above equation can be solved for ϵ, that yields $\epsilon = 1.87$. Note that a typical value for elasticity of substitution in growth literature is 2, which is close to the calibrated value. Moreover, this paper has fixed operating cost which must be considered in the calculation of average markups if targeted. In fact, the average markup for large firms in the paper is similar markups in the macroeconomic literature.

In order to identify ϕ, the paper starts with equation (2.29) on the BGP:

$$\frac{s}{\gamma}\frac{2 - \xi}{\xi} - \rho - \delta - \frac{\phi n(1 - \rho\gamma)}{\gamma L} + \frac{1 - \rho\gamma}{\alpha\gamma}\Big(\rho + \delta\Big) = 0, \tag{2.34}$$

which contains two unknowns: the parameter ϕ and the endogenous variable n. This equation yields ϕn, and identification of ϕ comes from the size of large firms. Notice that a large firm has both production and R&D employment, so we have $\ell = L_x + L_z$. One can write this expression in terms of known parameters, targeted moments, and n.

$$\ell = \frac{X}{Z} + \phi + \frac{z}{\alpha(\frac{n}{L})}$$

$$\ell = \frac{PX}{PZ} + \phi + \frac{z}{\alpha(\frac{n}{L})}$$

$$\ell = \frac{\mathscr{Y}}{n} s \frac{\xi - 1}{\xi} + \phi + \frac{z}{\alpha(\frac{n}{L})}. \tag{2.35}$$

Equations (2.34) and (2.35) can be solved together for ϕ and endogenous variable $\frac{n}{L}$, that yields $\phi = 247$.

Finally, identification of β comes from the fact that the market share of large firms s, and the measure of large firms n are connected via (2.27), and from the identification of ϕ we already know the value of endogenous variable $\frac{n}{L}$ in terms of other known parameters and targeted moments. Tables 2.1 and 2.2 summarize the targeted moments and the resulting calibrated parameters.

Table 2.1: Targeted moments (annual).

moment	**data**
Risk Free Rate	3.0%
Large Firms' Average Death Rate	5.7%
(Dividend-to-Consumption)/Dividend-Yield	2.8
R&D-to-GDP ratio	2.5%
GDP per capita Growth Rate	2.0%
Large Firms' Median Size	500
Large Firms' Production Share	60%

Table 2.2: Calibrated parameters (annual).

ρ	δ	γ	α	β	ϵ	ϕ
0.030	0.057	2.80	0.632	209	1.87	247

2.6 Quantitative Exercises

This section presents two counterfactual exercises for the long-run, and the medium-run. In the long-run exercise, the paper presents the quantitative predictions of the model for the increase in the market share of large firms. The medium-run exercise investigates the effect of an unexpected transitory supply shock.

2.6.1 Long-run Exercise

The market share of large firms has been following an upward trend since the mid-eighties. Critically, the share of large firms in the model is a linear function of the size of large firms (in steady-state, see the calibration section). But the size of large firms in the model is pinned down by the parameter ϕ. An increase in ϕ can be interpreted as mergers and acquisitions in reduced form, *i.e.*, as two equal size firms merge, their fixed operating cost doubles (while their profit more than doubles, due to the increase in markups). Thus, if there was no merger cost, firms would want to merge indefinitely. However, the government controls this process through the anti-trust laws. This is similar to government setting the parameter ϕ, that in turn regulates the size of large firms. Moreover, policy papers (CEA, 2016), and academic studies (Peltzman, 2014) have documented that the anti-trust laws started to loosen with the unset of the 'deregulation' period, and this process has gradually continued until today.

The paper assumes that economy is given a one-time unexpected shock at the year 1985, that is the announcement of the time path of $\phi(t)$ for the next three decades. Namely, it is announced that $\phi(t)$ starts to increase with a predetermined path from 1985 to 2017, at which level ϕ stops forever. The paper finds this path such that the endogenous time series of the market share of large firms follows a trend that matches the data. Then, the paper looks at how the productivity has responded to this trend in the market share of large firms (recall that productivity responds to ϕ only through s). The results are depicted in graph 2.7. Notice that

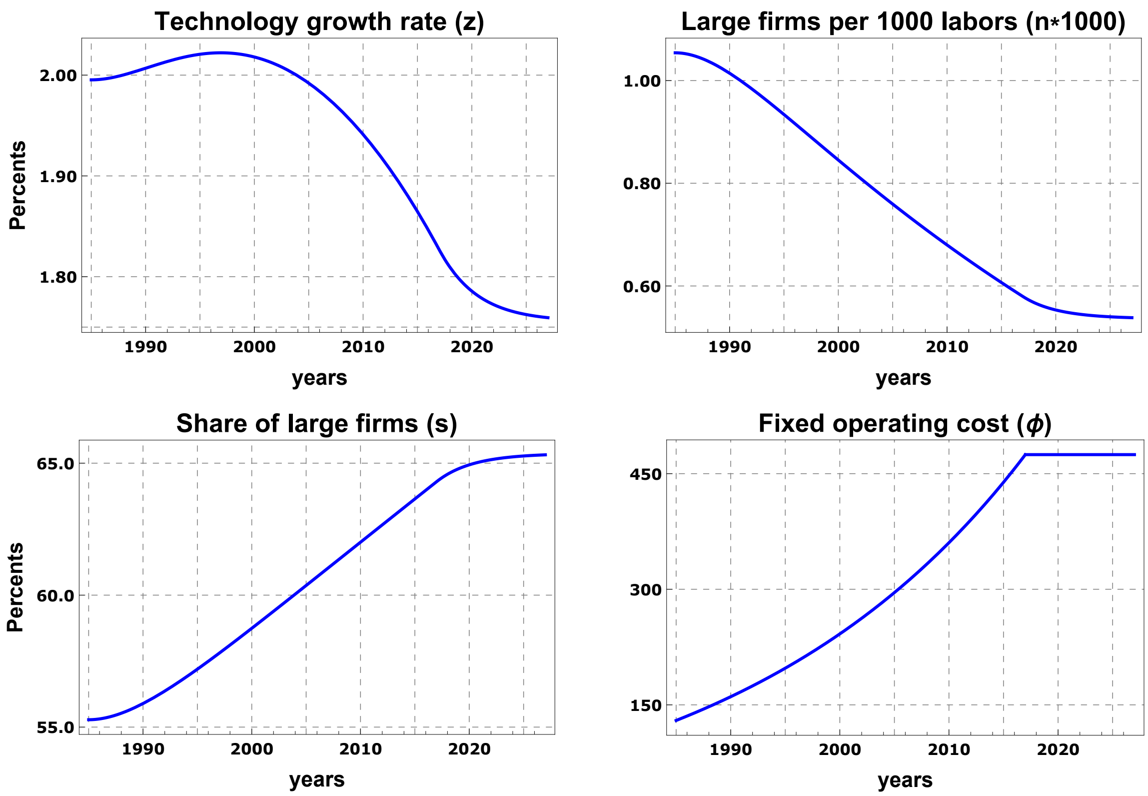

FIGURE 2.7: Response of productivity growth to changes in market structure.

although the changes in ϕ stops at 2017, the full effect on the productivity growth takes another ten years to materialize. Moreover, an interesting prediction of the model is that productivity growth starts to increase up to the late nineties, and then has a downward trend that peters out after the market share loses its trend. The reason is that at the beginning of the period, the U.S. economy is on the left side of the inverted-U relation between productivity growth and share of large firms (see figure 2.5). However, as the share of large firms increase, the economy goes over the maximum and falls off the other side.

The total loss in the productivity growth from the highest point at 1998 to the lowest point is about 28 basis points, and about 23 basis points drop are materialized between 1998-2017. To put it in perspective, the household would give up about 10% of its lifetime consumption to avoid this loss in productivity growth. As an extension of this counterfactual exercise, one can ask what would happen if the trend in the market share of large firms continued the same trend for another decade (*i.e.*, from 2017 to 2027). Simulation shows that there will be about another 28 basis points drop if the trend continues unchanged. This exercise suggests that policy makers should pay attention to possible ramifications of further slow down due to the current trends in the market structure.

As an external validation, it is useful to compare the prediction of the model (that is calibrated to macro data), with the reduced form result from the micro-data at the empirical section. It is enough to simulate the R&D-intensity and employment share of large firms (ESOLF), and draw the Log(R&D-intensity) versus Log(ESOLF), the same as the left panel of figure 2.2, and compare it with the reduced-form regression shown at the empirical section. This comparison is shown in figure 2.8. It can be seen that the model is in agreement with the micro-data. Note that the model also predicts other changes in the market structure that were not targeted, and can be compared to data. For example, the model predicts that the size of large firms has more than doubled in the past twenty years, which is in agreement with the CRSP data. Also, the model predicts that markups were on the rise, entry rate was on the fall, and so on. Of course this is a very parsimonious model and is not designed to match all the trends perfectly, but it is possible to create a similar model with heterogeneous industries that offers more flexibility, and goes after all these trends at the same time.

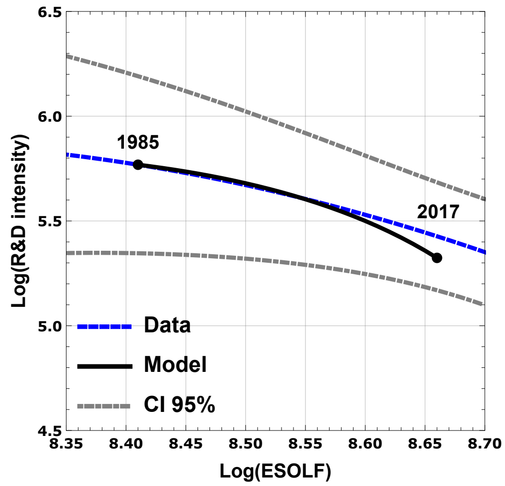

FIGURE 2.8: Model versus micro-data

2.6.2 Medium-run Exercise

This section investigates the impulse responses of a small supply shock to the economy. Recall from equation (3.3) that a decrease in ψ means that the household has to work more wasteful hours for the government. Hence, a negative shock to ψ means less productive labor hours for the economy. A supply shock changes the production possibility frontier, and since labor is the only factor of production in this economy, and all production functions are linear in labor, a decrease in parameter ψ is a supply shock, that is identical to a negative total factor productivity (TFP) shock. This exercise gives a unexpected negative transitory supply shock to the economy, that mimics a crisis. The point of this exercise is to compare the response of the economy at two different levels of concentration, *i.e.*, for two different levels of ϕ. Figure 2.9 shows the impulse responses for a counterfactual exercise that compares the U.S. economy at 2001 versus 2007. Notice that the drop in the entry is much more pronounced at 2007. In fact, the model predicts that the recession at 2007 (if caused by a supply shock) would have followed by much larger drop in the number of large firms, and a slower recovery, that also affects negatively the measure of public technology. Moreover, the response of consumption growth at 2007 shows much more propagation compared to 2001. The rest of this section explains why

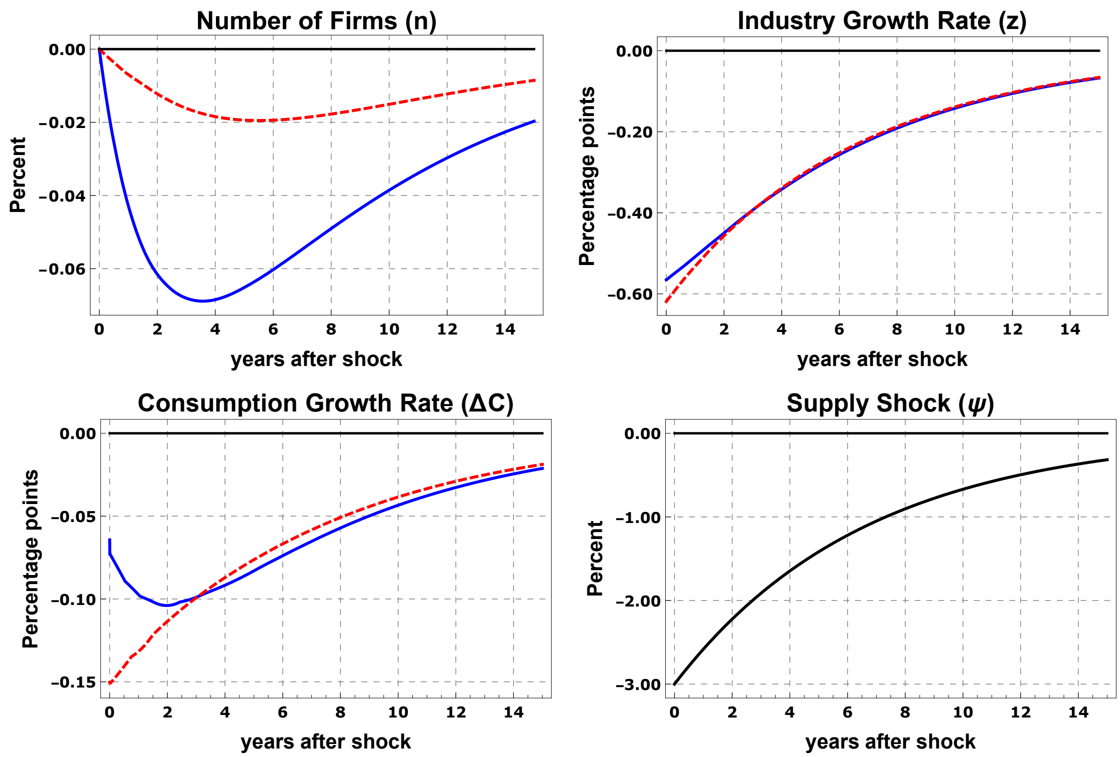

FIGURE 2.9: Comparison: 2001 ($s = 0.61$, dashed-red) vs 2007 ($s = 0.62$, solid-blue)

more concentrated economies respond to supply shocks with deeper recessions and longer recoveries.

A negative supply shocks lowers the profit of large firms, which in turn lowers the return to entry and results in net exit. Recall from lemma 1 that a smaller measure of large firms means a larger market share of large firms. This is also verified by data in figure 2.10, where it is showed that the employment share of large firms is highly counter-cyclical. In fact, the correlation of NBER recessions and HP-filtered ESOLF is the same as the correlation of NBER recessions and HP-filtered GDP over the same period (about 0.55), and this is in contrast to the number of large firms, which is pro-cyclical. Thus, the share of large firms goes up during the recessions both in the model and in the data.

It is easier to see the effect of an increase in the market share s by comparing two economies on different sides on the inverted-U function $z(s)$. This is shown in figure 2.11. A negative shock to ψ in the medium-run shifts the curve down (shown as the black curve). Then, there are two forces that affect $z(s)$. Since ψ is going back to its original value, the curve is shifting up, back to its original position, that is shown by the up arrows in the graph. However, in the medium-run s increases and then goes back to its original place. This means that as the curve shifts up, along the curve, s moves to the right and then goes back. Thus, if the steady-state s is on the left hand side of the hump, there exists an additional positive force on z, whereas for the steady-state s on the right hand side of the hump, this creates an additional negative effect. This affects the speed of recovery since for the s on the left side of the hump, the growth rate overshoots and approaches its long-run level from above. In contrast, for the s on the right side of the bump, the growth rate approaches to its long-run level from below, resulting in a slower recovery.

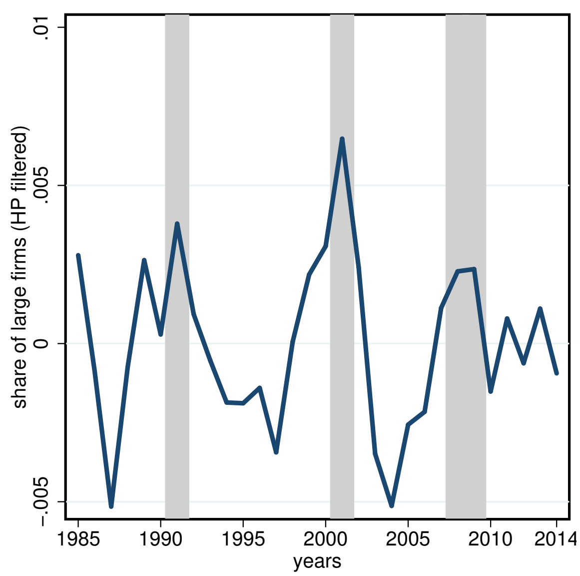

FIGURE 2.10: Share of large firms is highly countercyclical.

The rise in the market share also affects the amplification of supply shocks. In particular, a larger market share means a larger markup that multiplies the supply shock. This in turn means that a negative supply shock reduces a large firms' profit more, and hence the return to entry is reduced more in more concentrated economies. This creates a larger exit rate when the shock impacts the economy. As a result, a negative supply shock creates a deeper recession in more concentrated economies.

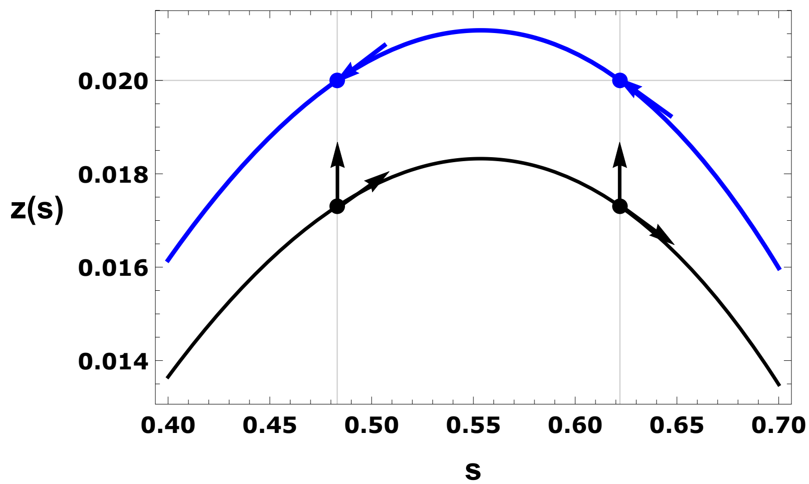

FIGURE 2.11: Unexpected negative transitory supply shock: different initial points.

2.7 Conclusion

The paper uses the market share of large firms as a measure to show that over the past three decades the U.S. economy has become more concentrated. Also, the empirical analysis shows an inverted-U relationship between the R&D-intensity of large firms and their market share. In order to investigate the effect of this change in market structure on labor productivity growth, the paper develops an endogenous growth model that focuses on the competition between large and small firms within industries. In part, large firms invest in R&D to lower their marginal cost of production and acquire more shares at the expense of small firms. The paper shows that the large firms' incentive to engage in R&D investment has in inverted-U relationship with their market share, just as the data suggests.

The model is calibrated to match the moments of U.S. aggregate variables. Simulation shows that as the market share of large firms increased since the mid eighties, the productivity growth increased until the late nineties and declined since then. The model associates 28 basis points loss in annual productivity growth rate to increase in the market share of large firms in the past three decades. Also, if the increasing trend in the market share of large firms continues unchanged, the model predicts that there will be another 28 basis points drop in productivity growth in the next decade. To put it in perspective, the household gives up 10% of its lifetime consumption to avoid this drop in productivity growth. Importantly, the model also shows that in the medium-run, impulse response to an unexpected transitory negative supply shock can be very different in two economies with different levels of market share of large firms. Particularly, a more concentrated economy experiences a deeper recession and a slower recovery.

3

Implications of Tax Policy for Innovation and Aggregate Productivity Growth (with Domenico Ferraro and Pietro Peretto)

3.1 Introduction

Economists have long recognized the critical role played by tax policy in determining short- and long-term rates of economic growth. Yet, our understanding of the transmission mechanisms of changes in individual and corporate income tax rates remains incomplete. Recently, the debate in the aftermath of the Great Recession of 2007-2009 has led to renewed interest in understanding the aggregate implications of tax policy, and more generally tax-induced distortions.

The 2007-2009 recession and the ensuing weak recovery has been characterized by a large and persistent decline in the labor input: The employment to population ratio fell by 6.4 percent from peak to trough (2007-Q4 to 2009-Q3) and it remains below pre-recession levels due to the continuing downward trend in labor force participation started in the late-2000s. Building on these observations, recent research has argued that policy-induced labor market distortions are a key driver of the movements in the labor input during the recession and its aftermath (see Mulligan, 2010; Ohanian, 2010).

Since 2004 measured growth in labor productivity and total factor productivity (TFP) has slowed down (see Syverson, 2016; Cette et al., 2016). Understanding the origins of such productivity slowdown requires a theory of the aggregate "effective labor input." Endogenous growth theory is a natural candidate.

In this paper, we examine the *quantitative* impact of income taxation on innovation and aggregate productivity growth in a quantitative version of the Schumpeterian model of innovation-led growth. Prominent feature of the theory is the interplay between product and quality innovation: entrant firms create new products whereas incumbent firms improve own existing products. Recent empirical evidence based on establishment-level data by Garcia-Macia et al. (2016) suggests that nearly 77 percent of product innovation in the United States consists of product improvements by incumbents, whereas the introduction of new varieties by either entrants or incumbents accounts for 4.4 percent. The remaining share is accounted by creative destruction. We adopt a formulation of the theory in which market-size effects are sterilized in the long-run through a process of product proliferation that fragments the aggregate market into submarkets whose size does not increase with the size of the workforce (see Peretto, 1998, 1999). Yet, market-size effects are key to understanding the transmission of tax policy to innovation and aggregate productivity growth in the short-run.

Though Schumpeterian growth theory has been fruitfully used to shed light on numerous aspects of the growth process (see Aghion et al., 2013, for a survey article), the quantitative implications of tax policy in this extended class of models are largely unexplored. Here we aim at filling this gap. To this goal, we focus on two central questions:

(i) What is the quantitative impact of permanent and temporary changes in individual income (labor income, dividends and capital gains) and corporate income tax rates?

(ii) What is the transmission mechanism of tax policy to firms' investment in innovation and thereby to aggregate productivity and real GDP growth?

To explain the key economic mechanisms driving the technology-policy interactions at play, it is useful to describe the structure of the model. The model combines product with quality-improving innovation. A a result, the theory nests Schumpeterian models based on the Quality Ladder framework, such as those described in Grossman and Helpman (1991b), Aghion and Howitt (1992), and Klette and Kortum (2004), and models based on the Expanding Variety framework of Romer (1990), such as those described in Grossman and Helpman (1991a). By using a model in which both types of innovation arise in equilibrium of a decentralized economy, one can start to understand the aggregate implications of technology-policy interactions more rigorously.

We consider an economy inhabited by a stand-in household that faces a consumption and savings decision: it chooses consumption, labor supply, and savings by freely borrowing and lending in a spot asset market. Household's income consists of returns on financial assets (corporate equity) and on risk-free bond holdings, labor income, and government transfers.

The production side of the economy consists of two sectors: (i) the final good sector; and (ii) the corporate sector. The final good sector consists of a representative competitive firm that demands intermediate goods and labor services to produce a homogeneous final good. The corporate sector is monopolistically competitive and it is the source of long-term growth in TFP and real GDP per capita. We associate firms in the corporate sector with Schedule C corporations in the U.S. federal tax code. For tax purposes, C corporations are considered separate legal entities from their shareholders. As a result, income generated by C corporations is subject to double taxation: business income is taxed at the corporate level as profits and it is taxed again at the individual level as distributed dividends.

The market structure of the corporate sector is endogenous: number of firms and firm size are jointly determined in free-entry equilibrium. Entry in the corporate sector requires payment of a sunk cost. Upon entry, firms produce intermediate goods that are vertically differentiated by quality. They also invest in research and development (R&D) to improve the quality of their products. R&D at the firm level contributes to the pool of public knowledge that benefits the final good sector in terms of increased TFP (or, equivalently, reduction of unit production costs). This process is self-sustaining and generates exponential growth in the long-run when entry stops and the economy settles into a stable industrial structure. In the model, the growth rate of TFP and thereby real GDP along the balanced growth path (BGP) is driven by product quality improvements by incumbent firms. The introduction of new products by entrant firms achieves instead sterilization of market-size effects when the economy settles on such BGP.

The government purchases final goods (government spending) and levies proportional tax rates on private consumption, individual income (labor income, dividends and capital gains), and corporate income. Lump-sum transfers to the household adjust to balance the government budget on a period-by-period basis.

To examine the quantitative implications of the theory, we calibrate the model to salient features of U.S. data. We construct measures of average effective tax rates on individual and corporate income that we use as model inputs. The results suggest that endogenous movements in TFP constitute a quantitatively important channel for the transmission of tax policy to real GDP growth. Endogenous market structure plays a key role in propagation.

To explain the transmission mechanism of tax policy embodied in the model, we first discuss the quantitative impact of constant tax rates along the balanced growth path (BGP) of the economy, then we turn to the effects of time-varying tax rates.

Long-term rates of TFP growth are unaffected by labor income tax rates. The mechanism yielding this result hinges on the sterilization of market-size effects: given the mass of firms, labor income tax rates affect demand for intermediate goods through the determination of the labor input, which in turn determines the size of the corporate sector, firm market share, and so R&D investment at the firm and aggregate level. Everything else equal, this would have long-term growth effects. Yet, as the size and so the profitability of incumbent firms change, the number of firms endogenously adjusts to bring the economy back to the initial long-term level of firm size, thereby sterilizing the long-term growth effects of labor income tax rates. Long-term rates of TFP growth are instead affected by asset and corporate income taxation: tax rates levied on dividends and capital gains at the individual level and on profits at the corporate level, disturb equilibrium arbitrage conditions that drive household saving, firms' entry and R&D investment decisions. These effects are quantitatively important.

A 1 percentage point (pp) cut in the tax rate on capital gains raises long-run growth by approximately 0.2 percentage points. The capital gains tax is effectively a tax on firm growth, such that a tax cut sharpens the incentives to R&D investment of incumbent firms. Along the new BGP, the number of firms is lower than the previous level, leading then to a more concentrated market structure. By contrast, an equally-sized 1 pp cut in dividend and corporate income tax rates reduces long-run growth by approximately 0.6 and 0.5 percentage points, respectively. A cut in either tax rate raises the rate of return to entry. The new BGP features then a larger number of firms, which stifles the R&D incentives of incumbent firms and thereby the growth rate of quality improvement and real GDP growth.

Time-varying tax rates on individual and corporate income have quantitatively large effects on aggregate quantities. In the model, quality-improving innovation is driven by the forward-looking investment behavior of the corporate sector. In deciding how much to investment in R&D, a firm trades off the cost of diverting resources from current (before-tax) operating profit with the benefit of reducing unit production costs in the future. Movements in tax rates act as *intertemporal disturbances* to this trade-off.

To capture the dynamic response of the economy to an unanticipated and temporary tax cut, we rely on impulse response functions (IRFs). IRFs represent a coherent way to describe the propagation mechanism embodied in the model. Temporary changes in tax rates have permanent effects on the level of real GDP per capita. Endogenous technical progress is key to understanding propagation. The response of aggregate R&D investment to the tax change feeds into a temporary acceleration or deceleration in the rate of product quality improvement, which cumulates into permanent gains or losses of output.

In response to a 1 pp cut in the labor tax rate, the labor input raises on impact, it then reverts back to the initial steady-state level mimicking the dynamics of the tax shock. The temporary expansion in equilibrium labor feeds into a temporary expansion in the aggregate demand for intermediate goods production. These transitional market-size effects stimulate aggregate R&D investment in the corporate sector and thereby spur a temporary acceleration of labor productivity and TFP growth. As a result, real GDP sluggishly raises during the transition dynamics and settles on an approximately 1.6 percent higher level relative to the previous trend. During the transition dynamics, firms' entry rate falls below the steady-state level, such that the number of firms in the corporate sector temporarily declines and slowly reverts back to the initial steady-state level. The response of the number of firms is U-shaped reflecting the internal propagation embodied in the model.

The dynamic responses to the dividend and corporate income tax cuts are comparable both in terms of transmission mechanism and of sign and magnitude of the overall effect on aggregate quantities. In response to a 1 pp cut in either tax rate, aggregate R&D investment temporarily declines below the long-run level, leading to a temporary deceleration in labor productivity and TFP growth. Such a deceleration in aggregate productivity leaves a sizable permanent effect on the level of real GDP, that settles on an approximately 5 percent lower level relative to previous trend. By contrast, in response to an equally-sized cut in the tax rate on capital gains, the economy experiences a temporary acceleration in aggregate productivity growth, that translates into a roughly 5 percent higher level of real GDP relative to previous trend.

The rest of the paper is organized as follows. In Section 3.2, we revisit some basic facts on post-war fiscal policy in the United States. In Section 3.3, we present the model. In Section 3.4, we discuss the transmission mechanism of tax policy embodied in the model. In Section 3.5, we present the quantitative implications for the U.S. economy. In Section 3.6, we quantitatively evaluate a tax reform based on a flat individual income tax. Finally, Section 3.7 concludes.

3.2 Post-WWII Fiscal Policy in the United States

To study the effects of tax policy on economic activity, we first need to construct time series for tax rates and government spending. We then need to specify expectations of the private sector about future policy. Here, we describe in detail how we construct these model inputs and relate them to the U.S. fiscal policy since World War II. (See Appendix B.2 for details on data construction, definitions and sources.)

The main source of data is the national income and product accounts (NIPA) released by the Bureau of Economic Analysis (BEA). Our approach of calculating average *effective* tax rates closely follows that of Mendoza et al. (1997). We aggregate all levels of the government (federal, state and local) into one general government sector. We categorize individual income as labor income and asset income (dividends and capital gains) and profits of Schedule C corporations as corporate income.

3.2.1 Individual Income Tax

In the model, individual income consists of labor and asset income (dividends and capital gains). In the U.S. tax code, these different sources of income are taxed at different rates.

Labor income tax. The tax rate on labor income used in the model, τ_t^l, is the average labor income tax rate (ALITR), that is estimated as

$$\text{ALITR} = \frac{\text{APITR} \times (\text{WSA} + \text{PRI}/2) + \text{CSI}}{\text{CEM} + \text{PRI}/2},$$

where APITR is the average personal income tax rate, WSA is wages and salaries, PRI is proprietors' income, CSI is contributions for government social insurance, and CEM is compensation of employees. The APITR is estimated as

$$\text{APITR} = \frac{\text{PIT}}{\text{WSA} + \text{PRI}/2 + \text{CI}},$$

where PIT is personal income taxes, that consists of federal personal income taxes and state and local personal income taxes, CI = PRI/2 + RI + DI + NI is capital income, RI is rental income, DI is net dividends, and NI is net interests. As discussed in Joines (1981), the imputation of proprietor's income to capital and labor income is somewhat arbitrary. Here we follow Jones (2002) and split proprietor's income evenly between capital and labor income. The source of the data is NIPA. (See Appendix B.2 for details on data sources and definitions related to the U.S. national accounts.) For the post-war period, 1946-2014, the mean ALITR is 20.6 percent. Panel A of Figure B.1 shows the time series for ALITR. The series shows a marked upward trend since the early-1950s. The ALITR was 15 percent in the early-1950s, but it has steadily raised to the 25 percent in 2014.

Dividend income tax. The tax rate on distributed dividends used in the model, τ_t^d, is the average marginal dividend income tax rate (AMDITR). The source of the data is Poterba (2004, p. 172, Table 1). AMDITRs after 1960 are based on tabulations from the NBER TAXSIM model, and on data from the U.S. Department of the Treasury, Statistics of Income (SOI), for earlier years. AMDITR includes the federal marginal income tax rate plus an estimate of the state marginal income tax rate, net of federal income tax deductibility. For the period 1946-2003, the mean AMDITR is 39.5 percent. Panel C of Figure B.1 shows the time series for AMDITR. The AMDITR was above 40 percent from 1946 to 1980. It starts declining in the early-1980s; it fluctuates in the 29-34 percent range until 2002 to reach the post-WWII trough of 18.5 percent in 2003. This substantial drop in AMDITRs is the result of the cuts in statutory tax rates on dividends prescribed by the Jobs and Growth Tax Relief Reconciliation Act (JGTRRA) of 2003.

Capital gains tax. The tax rate on capital gains used in the model, τ_t^v, is the average capital gains tax rate (ACGTR). The source of the data is the U.S. Department of the Treasury, Office of Tax Analysis. For the period 1954-2013, the mean ACGTR is 17 percent. Panel D of Figure B.1 shows the time series for ACGTR. The ACGTR is approximately constant at the 15 percent level from the mid-1950s to the mid-1980s. It raises in the late-1980s due to the Tax Reform Act of 1986, which prescribed that capital gains faced the same tax rate as ordinary income. The ACGTR drops from 25 percent to 20 percent in 2000 due to the Taxpayer Relief Act of 1997, which reduced the statutory top marginal tax rate on capital gains from 28 percent to 20 percent. ACGTRs were further reduced by the Economic Growth and Tax Relief Reconciliation Act (EGTRRA) of 2001 and the JGTRRA of 2003.

3.2.2 Corporate Income Tax

The tax rate on corporate profits used in the model, τ_t^{π}, is the average corporate income tax rate (ACITR), that is estimated as ACITR = CT/CP, where CT is federal, state and local taxes on corporate income (excluding Federal Reserve banks) and CP is the corporate income tax base, that consists of corporate profits (excluding Federal Reserve banks' profits). The source of the data is NIPA. (See Appendix B.2 for details on data sources and definitions related to the U.S. national accounts.) For the post-war period, 1946-2014, the mean ACITR is 32 percent. Panel B of Figure B.1 shows the time series for ACITR. The series shows a marked downward trend since the early-1950s. The ACITR was as high as 54.5 percent in 1951, but it has steadily declined since then to a low of 19.3 percent in 2014.

3.2.3 Indirect Business Tax

Included in the analysis are also indirect business taxes on consumption. The tax rate on private consumption used in the model, τ_t^{c}, is the average consumption tax rate (ACTR), that is estimated as

$$\mathrm{ACTR} = \frac{\mathrm{TPI} - \mathrm{PRT}}{\mathrm{PCE} - (\mathrm{TPI} - \mathrm{PRT})},$$

where TPI is taxes on production and imports, PRT is property taxes, and PCE is personal consumption expenditures on durables, nondurables, and services. Taxes on production and imports consists of federal excise taxes and custom duties and of state and local sales taxes, property taxes (including residential real estate taxes), motor vehicle licenses, severance taxes, special assessments, and other taxes. The source of the data is NIPA. (See Appendix B.2 for details on data sources and definitions related to the U.S. national accounts.) Panel E of Figure B.1 shows the time series for ACTR. For the post-war period, the mean ACTR is 8 percent. The ACTR has been nearly constant at 9 percent from the early-1950s to the early-1970s, but it has declined since then to 6.8 percent in 2014.

3.2.4 Government Spending

In addition to time-varying tax rates, the private sector (household and corporate sector) also faces time-varying government spending. Government spending is modeled as a share of real GDP per capita. The spending-to-GDP ratio (GRATIO) used in the model, g_t, is estimated as GRATIO = GOV/GDP, where GOV is government consumption expenditures and gross investment, that includes federal (national defense plus nondefense), state and local government level, and GDP is gross domestic product. The source of the data is NIPA. (See Appendix B.2 for details on data sources and definitions related to the U.S. national accounts.) Panel F of Figure B.1 shows the time series for GRATIO. For the post-war period, the mean GRATIO is nearly 21 percent. The GRATIO was below 20 percent until 1950. It sharply raised from 17 percent in 1950 to the post-WWII peak of nearly 25 percent in 1953. Such a surge in government spending is the result of the increase in national defense expenditure due to the Korean War of 1950-1953. To meet the financing needs for defense expenditure, the Revenue Act of 1950 raised the statutory top corporate income tax rate from 38 to 42 percent in 1950 and to 52 percent in 1952. Since the mid-1950s, government spending has slowly declined and represents 18 percent of GDP in 2014.

3.2.5 Fiscal Policy Expectations

Before we can simulate equilibrium paths for the model economy, we need to describe private sector's expectations about future government spending and taxes. Thus, here we detail our assumptions, at least for our benchmark policy expectations. Specifically, we fit low-order autoregressive processes to actual data for tax rates (τ_t^c, τ_t^l, τ_t^d, τ_t^v, and τ_t^π) and government spending to GDP ratio, g_t:

$$x_t = d_t + \sum_{j=1}^{p} \rho_j^x x_{t-j} + \sigma_\epsilon^x \epsilon_t, \quad \text{with} \quad \epsilon_t \overset{iid}{\sim} \mathcal{N}(0,1), \tag{3.1}$$

where the deterministic term d_t contains a constant, d_0, and nth-order polynomial trends in time, d_t^n. Lag length p is selected via the Akaike Information Criterion (AIC). For the stochastic process in (3.1), the autoregressive parameters ρ_j^x control the persistence of the shocks to the tax rates and to the government spending to GDP ratio. The parameter σ_ϵ^x controls the volatility of the innovations ϵ_t. Table B.1 summarizes the estimation results.

3.3 Model

In this section, we present the model: preferences, technologies, budget and information sets.

Environment. We consider a closed economy inhabited by a stand-in household that supplies labor services in a spot labor market. The household faces a standard consumption-savings decision: it chooses consumption, labor supply, and savings by freely borrowing and lending in a spot asset market. Household's income consists of returns on financial assets (corporate equity) and on risk-free bond holdings, labor income, and government transfers.

The production side of the economy consists of two sectors: (i) the final good sector; and (ii) the corporate sector. The final good sector consists of a representative competitive firm that demands intermediate goods and labor services to produce a homogeneous final good. The corporate sector is monopolistically competitive and it is the source of long-run growth in total factor productivity (TFP) and real gross domestic product (GDP) per capita. We associate firms in the corporate sector with Schedule C corporations in the U.S. federal tax code. For tax purposes, C corporations are considered separate legal entities from their shareholders. As a result, income generated by C corporations is subject to double taxation: business income is taxed at the corporate level as profits and it is taxed again at the individual level when it is distributed to owners as dividends.

The market structure of the corporate sector is endogenous: the total mass of firms and firm size are jointly determined in free-entry equilibrium. Entry in the corporate sector requires payment of a sunk cost. Upon entry ("horizontal innovation"), firms produce intermediate goods that are vertically differentiated by quality. They also invest in research and development (R&D) to improve the quality of their products ("vertical innovation"). R&D at the firm level contributes to the pool of public knowledge that in turn benefits the final good sector in terms of increased TFP (or, equivalently, reduction of unit production costs). This process is self-sustaining and generates exponential growth in the long-run when entry stops and the economy settles into a stable industrial structure.

Finally, the government purchases the final good (government consumption) and levies proportional tax rates on private consumption, individual income (labor income, dividends and capital gains), and corporate profits. Lump-sum transfers adjust to balance the budget on a period-by-period basis. Note that allowing the government to issue public debt that pays a risk-free interest rate would leave the equilibrium of the model unchanged.

Timing convention. Time is discrete and indexed by $t \geqslant 0$. With the notation here, we adopt the following timing convention: the date t of a generic variable X_t (either control or state variable) indicates the point in time when X_t is chosen. Thus, predetermined variables are dated $t-1$ in time t equations and dated t in time $t+1$ equations.

3.3.1 Household Sector

The economy is inhabited by a stand-in household with a unit mass of infinitely-lived members. Each member is endowed with one unit of time and supplies labor services in a spot labor market. Household preferences are defined by the per-period utility function $u(c_t, l_t)$ that is separable in consumption per capita, c_t, and the fraction of time spent at work, l_t:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\ln c_t - \gamma \frac{l_t^{1+\vartheta}}{1+\vartheta} \right), \tag{3.2}$$

where $\mathbb{E}_0$ indicates the mathematical expectation conditional on the information set available at time zero. The parameter β is the subjective time discount factor, γ parametrizes the disutility of work, and ϑ is the inverse of the Frisch elasticity of labor supply.

The household can invest in risky financial assets (corporate equity), a_t, that pay a gross *after-tax* rate of return of $\tilde{R}_t^a$ and hold a risk-free bond, B_t, that pay a gross interest rate of R_t^b in period $t+1$. Asset income is then $\tilde{R}_t^a a_{t-1} + R_{t-1}^b B_{t-1}$. Labor income is $w_t l_t$, where w_t is the hourly wage that is determined in a competitive labor market. The household faces a proportional tax on consumption, τ_t^c, on labor income, τ_t^l, on dividend income, τ_t^d, and a capital gains tax (CGT), τ_t^v. And it receives lump-sum government transfers, Ω_t. Hence, the household's flow budget constraint is:

$$(1+\tau_t^c)c_t + a_t + B_t = (1-\tau_t^l)w_t l_t + \tilde{R}_t^a a_{t-1} + R_{t-1}^b B_{t-1} + \Omega_t. \tag{3.3}$$

At the start of period t, financial assets, $a_{t-1} = s_{t-1}\mathscr{V}_{t-1}$, consist of shares, s_{t-1}, of an "hedge fund" that aggregates equities of the entire corporate sector into an economy-wide portfolio whose ex-dividend market value (or price) is $\mathscr{V}_{t-1} =$

$\int_0^{N_{t-1}} V_{i,t-1}\, di$, where $V_{i,t-1}$ is the price of firm i's shares and N_{t-1} is the mass of firms (gross-of-death incumbents) in the corporate sector at the start of the period. The hedge fund takes the firm's share price $V_{i,t}$ as given.[1] At the end of period t, financial assets are $a_t = s_t \mathscr{V}_t$, with $\mathscr{V}_t = \int_0^{N_t} V_{i,t}\, di$, where N_t is the mass of firms at the end of the period, that is, the mass of net-of-death incumbents, $\tilde{N}_{t-1} \equiv (1-\delta)N_{t-1}$, plus the mass of new firms entering the corporate sector, $\Delta_{N,t}$: $N_t = (1-\delta)N_{t-1} + \Delta_{N,t}$, where δ is the per-period (exogenous) probability that each firm exits the corporate sector and $n \equiv \Delta_{N,t}/N_{t-1}$ is the firm's entry rate. Hence, $n - \delta$ is firm's net entry.[2]

The gross after-tax rate of return to the market portfolio, $\tilde{R}_t^a$, is the *average* of the gross after-tax rates of return to firm-level equity in the corporate sector, $R_{i,t}^a \equiv 1 + r_{i,t}^a$:

$$\tilde{R}_t^a \equiv \frac{1}{N_{t-1}} \int_0^{\tilde{N}_{t-1}} R_{i,t}^a di, \quad \text{with} \quad R_{i,t}^a \equiv 1 + \frac{(1-\tau_t^d)D_{i,t} + (1-\tau_t^v)\left(V_{i,t} - V_{i,t-1}\right)}{V_{i,t-1}}, \tag{3.4}$$

where $D_{i,t}$ indicates firm i's distributed dividends, and τ_t^d and τ_t^v are tax rates on distributed dividends and capital gains, respectively.

Household's problem. The household takes tax rates (τ_t^c, τ_t^l, τ_t^d, and τ_t^v) and prices (w_t, $\tilde{R}_t^a$, and R_t^b) as given and chooses the time path for consumption, c_t, labor supply, l_t, equity shares, s_t, and bond holdings, B_t, given financial assets, a_{t-1}, and risk-free bonds, B_{t-1}, from the previous period, to maximize lifetime utility in (3.2) subject to the budget constraint in (3.3). (Standard no-Ponzi game conditions on equity and bonds hold.)

[1] In this specification, the hedge fund charges no fees to the household. Alternatively, one could think of a competitive environment where the hedge fund charges fees, but it breaks even in a zero-profit equilibrium.

[2] $\delta > 0$ is required for the model to have symmetric dynamics in the neighborhood of the non-stochastic steady-state.

The household's maximization problem yields: (i) an intratemporal (static) condition,

$$\frac{u_l(c_t, l_t)}{u_c(c_t, l_t)} = -\frac{(1-\tau_t^l)}{(1+\tau_t^c)}\, w_t; \tag{3.5}$$

(ii) an intertemporal condition for bond holdings,

$$1 = \mathbb{E}_t\left[\beta\, \frac{u_c(c_{t+1}, l_{t+1})}{u_c(c_t, l_t)} \left(\frac{1+\tau_t^c}{1+\tau_{t+1}^c}\right) R_t^b\right]; \tag{3.6}$$

and (iii) an intertemporal condition for corporate equity's shares,

$$1 = \mathbb{E}_t\left[\beta\, \frac{u_c(c_{t+1}, l_{t+1})}{u_c(c_t, l_t)} \left(\frac{1+\tau_t^c}{1+\tau_{t+1}^c}\right) \tilde{R}_{t+1}^a\right]. \tag{3.7}$$

We stress that equations (3.6) and (3.7) are asset pricing equations that drive the consumption-saving decisions of the household, that we parsimoniously rewrite as $1 = \mathbb{E}_t\left[M_{t,t+1} R_t^b\right]$ and $1 = \mathbb{E}_t\left[M_{t,t+1} \tilde{R}_{t+1}^a\right]$, respectively, where $M_{t,t+1}$ is the consumption-tax-adjusted stochastic discount factor (SDF) between period t and $t+1$:

$$M_{t,t+1} \equiv \beta\, \frac{u_c(c_{t+1}, l_{t+1})}{u_c(c_t, l_t)} \left(\frac{1+\tau_t^c}{1+\tau_{t+1}^c}\right). \tag{3.8}$$

The expression in (3.8) shows that intertemporal disturbances in consumption taxes directly affect valuation of the risk-free bond and of risky claims on the corporate sector. Note that if $\tau_t^c = \tau_{t+1}^c$ for all $t \geqslant 0$ then consumption taxes have no intertemporal distortion.

3.3.2 Final Good Sector

The final good sector is competitive and consists of a representative firm (final producer) that demands intermediate inputs, $X_{i,t}$, that are vertically differentiated based on their *quality*, $Z_{i,t}$, and labor input, L_t, to produce a final good, Y_t, that we take as the numeraire. The price of the final good is then set to one. The final good has four different uses: (i) private and government consumption; (ii) production of intermediate goods; (iii) investment in the improvement of the quality of existing intermediate goods (quality upgrading); and (iv) investment in the creation of new intermediate goods (expanding variety). The technology for the production of the final good (gross output) is:

$$Y_t = \int_0^{\tilde{N}_{t-1}} X_{i,t}^{\theta} \left(Z_{i,t-1}^{\alpha} Z_{t-1}^{1-\alpha} \frac{L_t}{\tilde{N}_{t-1}^{\eta}} \right)^{1-\theta} di, \tag{3.9}$$

where $\tilde{N}_{t-1}$ is the mass of active firms at the start of period t, that also corresponds to the mass of intermediate goods available for purchase at the start of the period, and $X_{i,t}$ is the quantity of intermediate good i used in production. The parameter $\eta \leqslant 1$ captures the degree of congestion (or rivalry) of labor services across intermediate goods. On the one hand, for $\eta = 0$ there is no congestion as labor services can be shared by all intermediate goods with no productivity loss. This is a case of extreme economies of scope in the use of the labor input that in equilibrium manifest themselves as strong social increasing returns to product variety. On the other hand, for $\eta = 1$ there is full congestion. This is the case of no economies of scope and no social returns to variety.

The contribution of intermediate good i into the production process depends on good i's own quality, at the start of the period, $Z_{i,t-1}$, as well as on the average quality of intermediate goods, $Z_{t-1} = (1/\tilde{N}_{t-1}) \int_0^{\tilde{N}_{t-1}} Z_{i,t-1} di$. Productivity of the labor input depends on the overall quality of the intermediate goods used in production. This is the defining feature of *vertical product innovation*: higher-quality intermediate goods perform similar functions to those performed by lower-quality goods, but they increase the efficiency of the production process and, as a result, they reduce unit costs of production.

Final producer's problem. The final producer takes intermediate good i's own quality, $Z_{i,t-1}$, and average quality of intermediate goods, Z_{t-1}, as given and sets the value marginal product of each intermediate good i equal to its price, $p_{i,t}$, and the value marginal product of labor equal to the wage rate, w_t. As a result, the demand curve for intermediate goods is:

$$X_{i,t} = \left(\frac{\theta}{p_{i,t}}\right)^{\frac{1}{1-\theta}} Z_{i,t-1}^{\alpha} Z_{t-1}^{1-\alpha} \frac{L_t}{\tilde{N}_{t-1}^{\eta}}. \tag{3.10}$$

In the expression (3.10), quality indexes $Z_{i,t-1}$ and Z_{t-1} are multiplicative demand shifters: quality improvements of existing intermediate goods shift the demand curves for intermediate goods outward. And the resulting demand curve for the labor input is:

$$L_t = \left(\frac{1-\theta}{w_t}\right) Y_t. \tag{3.11}$$

Note that perfect competition in the final good sector and the production technology in (3.9) imply that the parameter $\theta < 1$ pins down the share of intermediate goods in gross output:

$$\int_0^{\tilde{N}_{t-1}} p_{i,t} X_{i,t} di = \theta Y_t. \tag{3.12}$$

We stress that in the model gross output differs from gross domestic product (GDP). The value of θ alongside other deep parameters, then, jointly determines the value of intermediate goods and labor income as a share of GDP.

3.3.3 Corporate Sector

The corporate sector is a monopolistically competitive industry and it consists of firms (intermediate producers) that produce intermediate goods that are vertically differentiated by quality. The market structure of the industry is endogenous: the total mass of firms and firm size are *jointly* determined in free-entry equilibrium. The intermediate producers also engage in quality upgrading by investing in research and development (R&D). Returns to R&D come in the form of monopoly rents in the imperfectly competitive product market. Quality upgrading (vertical innovation) is the source of long-run growth in income per capita.

Incumbent firms. An incumbent firm operates a technology that requires one unit of final good per unit of intermediate good produced and the payment of a fixed operating cost, ϕZ_{t-1}, in units of the final good.[3] Hence, firm i's gross cash flow (revenues minus production costs) is $F_{i,t} = X_{i,t}(p_{i,t} - 1) - \phi Z_{t-1}$, with $\phi > 0$, where $X_{i,t}$ and $p_{i,t}$ are output and unit output price, respectively. Intermediate producers take the average quality index Z_t as given. An incumbent firm can also upgrade the quality of the own intermediate good by investing in R&D, $I_{i,t}$, also in units of the final good:

$$Z_{i,t} = Z_{i,t-1} + I_{i,t}, \tag{3.13}$$

where we associate $I_{i,t}$ to business R&D expenditure. At the individual firm-level, incentives to R&D stem from the shape of the demand curve in equation (3.10): quality upgrading shifts the demand curve for the intermediate good outward which, everything else being equal, raises firm's profit. Before-tax operating profit is $\Pi_{i,t} = F_{i,t} - \sigma_t I_{i,t}$, where $0 \leqslant \sigma_t \leqslant 1$ allows for full/partial deductibility of R&D expendi-

[3] If $\phi = 0$ then expanding variety (horizontal innovation) becomes a source of long-run growth as in first-generation models of endogenous growth à la Romer (1990).

ture.[4] Operating profit $\Pi_{i,t}$ represents the tax base for the corporate income tax, τ_t^π. Hence, dividends are $D_{i,t} = (1-\tau_t^\pi)F_{i,t} - (1-\sigma_t\tau_t^\pi)I_{i,t}$.

The (incumbent) intermediate producer takes the demand curve for the intermediate good in (3.10), law of motion for quality upgrading in (3.13), and tax rates (τ_t^d, τ_t^v) as given and it chooses the time path for output prices, $p_{i,t}$, and R&D investment, $I_{i,t}$, given quality indexes $Z_{i,t-1}$ and Z_{t-1}, to maximize the cum-dividend value of the firm $\left(1-\tau_t^d\right)D_{i,t} + V_{i,t} - \tau_t^v\left(V_{i,t} - V_{i,t-1}\right)$. The ex-dividend value of the firm $V_{i,t}$ is the present discounted value (PDV) of net-of-tax rate dividends, where the discount factor is a function of the consumption-tax-adjusted SDF and of the capital gains tax rate, adjusted for the firms' survival probability:

$$V_{i,t} = \left(\frac{1}{1-\tau_t^v}\right)\mathbb{E}_t\sum_{j=1}^{\infty}\left(\prod_{k=1}^{j}\tilde{M}_{t+k-1,t+k}\right)\left(1-\tau_{t+j}^d\right)D_{i,t+j}, \tag{3.14}$$

where the look-alike discount factor $\tilde{M}_{t,t+k}$ is defined as

$$\tilde{M}_{t+k-1,t+k} \equiv \frac{(1-\delta)M_{t+k-1,t+k}(1-\tau_{t+k-1}^v)}{1-\mathbb{E}_{t+k-1}\left[(1-\delta)M_{t+k-1,t+k}\tau_{t+k}^v\right]}, \tag{3.15}$$

and $M_{t+k-1,t+k}$ is the consumption-tax-adjusted SDF, as defined in (3.8). Given the expression for the ex-dividend value of the firm in (3.14), the incumbent intermediate producer maximizes, then, the following cum-dividend firm value:

$$(1-\tau_t^d)D_{i,t} + \mathbb{E}_t\sum_{j=1}^{\infty}\left(\prod_{k=1}^{j}\tilde{M}_{t+k-1,t+k}\right)\left(1-\tau_{t+j}^d\right)D_{i,t+j} + \tau_t^v V_{i,t-1}. \tag{3.16}$$

Note that in the expression (3.16), the last term $\tau_t^v V_{i,t-1}$ on the right-hand side is irrelevant for the firm's value maximization problem, as it is independent of current

[4] In the U.S. tax code R&D expenditure is fully deductible from taxable corporate income, that is, $\sigma_t = 1$.

firm's choices.[5] The intermediate producer's maximization problem yields: (i) a constant markup over the marginal cost pricing rule,

$$p_{i,t} = \frac{1}{\theta} \quad \text{for all} \quad t \geqslant 0; \tag{3.17}$$

and (ii) an intertemporal condition that drives the R&D investment decision,

$$1 = \mathbb{E}_t \left\{ (1-\delta) M_{t,t+1} \left[\frac{(1-\tau_t^v)(1-\tau_{t+1}^d)(1-\tau_{t+1}^\pi)}{(1-\tau_t^d)(1-\tau_t^\pi)} \left[\left(\frac{1-\theta}{\theta} \right) \frac{\alpha X_{i,t+1}}{Z_{i,t}} + 1 \right] + \tau_{t+1}^v \right] \right\}. \tag{3.18}$$

Entrant firms. To set up a firm and enter the corporate sector, an entrepreneur must incur a sunk cost, νX_t, in units of the final good, where $X_t = (1/\tilde{N}_{t-1}) \int_0^{\tilde{N}_{t-1}} X_{i,t} di$ is the average quantity of intermediate goods. Specifically, the economy starts out with a given range of intermediate goods, each supplied by one firm. Because of the sunk cost, new firms cannot supply an existing good in Bertrand competition with the incumbent monopolists but must instead introduce a new intermediate good that expands product variety. Entry is positive if the ex-dividend value of the firm equals the sunk entry cost: $V_{i,t} = \nu X_t$ for all $t \geqslant 0$. The mass of new firms that enters the corporate sector in period t starts operating and paying out dividends from period $t+1$ onward. Entrants finance entry by issuing equity and enter at the average quality level. The latter is a simplifying assumption that preserves symmetry of equilibrium.

3.3.4 Government Sector

The government purchases final goods and finances spending by levying distortionary taxes and balances the budget period-by-period with lump-sum transfers. Hence,

[5] See Appendix B.3 for details on the derivation of the cum-dividend value of the firm in equation (3.16).

the government's budget constraint reads $G_t + \Omega_t = T_t$, where G_t is net-of-transfers government spending (or public consumption), Ω_t denotes lump-sum transfers, and T_t indicates total tax collections.

Government spending is modeled as a share of real GDP: $G_t = g_t \mathscr{Y}_t$, with $0 \leqslant g_t < 1$, where $\mathscr{Y}_t$ denotes real GDP. Note that government purchases of final goods are modeled as a "pure waste," as they do not affect either marginal utility of private consumption or production. Note also that there is no government-sponsored R&D spending. We focus then on the effects of distortionary taxation. Proportional tax rates are levied on individual income (labor income, dividends and capital gains), on corporate income (operating profits net of business R&D expenditure), and on private consumption expenditures. In the model, tax rates are modeled as low-order autoregressive (AR) stochastic processes to capture the inherent uncertainty in post-war U.S. tax policy. As argued in Section 3.2, we fit these AR processes to U.S. tax data. As a result, the expectations of the household and business sector in the model about future policy changes are tightly linked to the expectations of the private sector in the United States. Such a consistency between model and actual policy expectations is key to understanding the dynamic adjustment of the economy in response to changes in tax rates.

3.4 Transmission of Tax Policy in General Equilibrium

We now turn to the general equilibrium of the model. Specifically, we focus on the symmetric equilibrium where firm-level variables equal their corresponding mean values. A a result, we next adopt a more parsimonious notation where we drop the i subscript from the variables at the firm level. As an example, $X_t \equiv X_{i,t}$ denotes average intermediate good production. Market clearing in labor and asset markets requires $l_t = L_t$ and $a_t = \mathscr{V}_t$, respectively. Note that the aggregate market value of the corporate sector equals $\mathscr{V}_t = N_t V_t$, whereas the after-tax return to the market portfolio is $\tilde{R}^a_t = (1-\delta)R^a_t$. Market clearing in the goods market yields the aggregate resource constraint of the economy, such that output is either consumed or invested in activities that generate future income and product:

$$C_t + G_t + \mathscr{I}_t + \mathscr{Q}_t = Y_t, \tag{3.19}$$

where C_t and G_t are private and public consumption, respectively, $\mathscr{I}_t$ indicates investment (R&D expenditure and entry costs), and $\mathscr{Q}_t$ indicates intermediate expenses (intermediate inputs and operating costs).

3.4.1 National Income and Product Accounts

In the model, the aggregate resource constraint yields the following decomposition of gross output between gross domestic product (GDP) and intermediate expenses:

$$\underbrace{\underbrace{C_t + G_t}_{\substack{\text{private + public}\\ \text{consumption}}} + \underbrace{\tilde{N}_{t-1} I_t}_{\substack{\text{product quality}\\ \text{investment (R\&D)}}} + \underbrace{\nu X_t \Delta_{N,t}}_{\substack{\text{firm creation}\\ \text{investment}}}}_{\text{GDP}} + \underbrace{\underbrace{\tilde{N}_{t-1} X_t}_{\substack{\text{inputs}\\ \text{cost}}} + \underbrace{\phi \tilde{N}_{t-1} Z_{t-1}}_{\substack{\text{operating}\\ \text{costs}}}}_{\text{intermediate expenses}} = \underbrace{Y_t}_{\substack{\text{gross}\\ \text{output}}} . \tag{3.20}$$

As shown in expression (3.20), we include R&D investment in the calculation of GDP.[6] This is consistent with the current NIPA approach. Since the 2013 NIPA release, BEA recognizes expenditures by business, government, and nonprofit institutions on R&D as fixed assets, which are then recorded as investment in GDP. In the previous NIPA approach, expenditures on R&D by business—whether purchased from others or carried out in-house—were treated as intermediate expenses used up

[6] Research and development (R&D) is defined in the System of National Accounts (SNA) as "creative work undertaken on a systematic basis to increase the stock of knowledge, and use of this stock of knowledge for the purpose of discovering or developing new products, including improved versions or qualities of existing products, or discovering or developing new or more efficient processes of production" (see `http://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf`).

during production of other goods and services rather than as capital expenses that generate future income and product. (See Appendix B.3 for further details on the calculation of GDP in the model related to the U.S. national accounts.)

3.4.2 Determinants of the Labor Input

We now turn to discuss the *intratemporal* trade-offs that drive the determination of the labor input, and thereby the transmission of tax policy to the aggregate labor market.

In setting the supply of labor services, the stand-in household equates the marginal rate of substitution (MRS) between consumption and leisure to the effective price of leisure. In the economy here, the consumption good is the numeraire such that the wage rate represents the relative price of leisure to consumption. Consumption and labor income tax rates introduce a wedge between MRS and the wage rate:

$$\gamma L_t^{\vartheta} C_t = \left(\frac{1 - \tau_t^l}{1 + \tau_t^c} \right) w_t. \tag{3.21}$$

Expression (3.21) describes an upward-sloping labor supply curve, with a Frisch elasticity of $\epsilon^{\mathrm{F}} \equiv d \ln L_t / d \ln w_t = 1/\vartheta$. Notice that in the baseline formulation of model, tax revenues are only partially rebated to the household sector as they finance government consumption. Thus, changes in consumption and labor income tax rates have income effects.[7]

To provide insight into the determination of the labor input, and thereby its equilibrium response to tax changes, it is useful to combine the household's intratemporal condition for labor supply in equation (3.21) with the intratemporal condition for labor demand of the final good producer in equation (3.11), which yields:

[7] The Hicksian elasticity determines the impact of taxes in steady-state if tax revenues are rebated to the household sector as lump-sum transfers. If tax revenues are not rebated, or only partially rebated, tax changes have income effects and the Marshallian elasticity becomes the relevant parameter.

$$L_t^{1+\vartheta} = \frac{1-\theta}{\gamma} \left(\frac{1-\tau_t^l}{1+\tau_t^c} \right) \frac{Y_t}{C_t}. \tag{3.22}$$

Changes in tax rates levied on consumption, τ_t^c, and on labor income, τ_t^l, have a direct impact on the aggregate labor input, L_t, through labor supply considerations, and an indirect equilibrium effect through the aggregate consumption-to-output ratio, C_t/Y_t. The extent to which C_t/Y_t responds to changes in either τ_t^l or τ_t^c, or both, depends on the response of the corporate sector, which takes place through changes in entrants' investment in firm creation (net firms' entry/exit) and incumbents' investment in R&D. Notice that the tax rates levied on individual asset income and corporate profits also affect the labor input, but only through the determination of the aggregate consumption-to-output ratio.

3.4.3 Determinants of Product and Quality Innovation

Next, we turn to study the *intertemporal* trade-offs that drive product and quality innovation, and thereby the transmission of tax policy to aggregate productivity and real GDP growth.

Aggregate R&D investment. In the model, quality-improving innovation is driven by the forward-looking investment behavior of the corporate sector. In deciding how much to investment in R&D, a typical firm trades off the cost of diverting resources from current (before-tax) operating profit with the benefit of reducing unit production costs in the future. Movements in tax rates act as intertemporal disturbances to this trade-off.

In symmetric equilibrium, the intertemporal first-order condition for quality-improving investment in equation (3.18) becomes:

$$1 = \mathbb{E}_t \left\{ (1-\delta) M_{t,t+1} \left[\frac{(1-\tau_t^v)(1-\tau_{t+1}^d)(1-\tau_{t+1}^\pi)}{(1-\tau_t^d)(1-\tau_t^\pi)} \left[\left(\frac{1-\theta}{\theta} \right) \alpha x_{t+1} + 1 \right] + \tau_{t+1}^v \right] \right\}, \tag{3.23}$$

where $x_{t+1} \equiv X_{t+1}/Z_t$ is the quality-adjusted measure of firm size, which determines firm's gross profitability through its relationship with the quality-adjusted gross cash flow (revenues minus variable and fixed production costs), $f_{t+1} \equiv F_{t+1}/Z_t$: $f_{t+1} = (p_{t+1} - 1)\, x_{t+1} - \phi$, where $p_{t+1} = 1/\theta$ is the unit output price of the typical firm in the corporate sector, and ϕ is the parameter governing the extent of fixed operating costs. Notice that the investment decision at the individual firm-level is a bang-bang problem, such that the intertemporal condition in equation (3.23) is to be interpreted as an investment "indifference" condition at the aggregate level. Everything else equal, unexpected changes in future tax rates mandate adjustment in current aggregate investment.

Consumption tax rates (through the effective SDF) and tax rates levied on dividends and profits distort corporate investment in R&D insofar as they vary over time. Put differently, the tax rates τ_t^c, τ_t^d, and τ_t^π drop from equation (3.23) to the extent that they are constant across two consecutive periods. This observation points to the potentially important role played by private sector expectations about the future path of tax rates. Volatile tax rates on consumption, dividends, and taxable corporate income directly distort the intertemporal allocation of corporate R&D expenditure.

By contrast, the tax rate levied on capital gains represents an intertemporal distortion irrespective of its variation over time. Intuitively, this happens because the capital gains tax (CGT) applies to *changes* in the market value of the firm; and the current R&D investment decision indeed affects the value of the firm tomorrow relative to today's level. The upshot of this argument is that, in the steady-state of the model with constant tax rates, CGT remains the only tax instrument determining the incentives to quality-improving innovation.

We further stress that the presence of consumption, asset, and corporate income tax rates, and the lack of the labor income tax rate in equation (3.23), reflects the different transmission channels of tax policy embodied in the model. Next, we provide some insight into the transmission mechanisms at play. First, changes in consumption tax rates directly affect the timing of investment decisions through changes in the effective SDF applied to risky cash flows. Everything else equal, a higher consumption tax rate tomorrow relative to today's level reduces the effective discount factor to current consumption, which deters current aggregate investment.

Second, tax rates levied on asset income (dividends and capital gains) directly affect the rate of return demanded by the household sector in order to hold claims on the corporate sector. The corporate sector as a whole needs then to change investment policy accordingly to guarantee the required rate of return to investors, as mandated by the equilibrium in the asset market. Third, changes in the corporate income tax rate affect the rate of return to the market portfolio held by the household sector by changing the intertemporal distribution of dividends.

Fourth, the tax rate levied on labor income has no direct effect on aggregate corporate investment, but only an indirect effect on firm size, and thereby on the gross profitability of the corporate sector through the determination of the labor input per active firm $f_{t+1} \propto L_{t+1}/\tilde{N}_t^{\eta} - \phi$. Few considerations are in order. Next period labor input, L_{t+1}, and number of active firms in the corporate sector, $\tilde{N}_t$, are equilibrium variables, that are out of control of the individual firm. Firms in the corporate sector take then future gross profitability, f_{t+1}, as a signal about the future prospects of aggregate demand for their products, X_t, and thereby of quality-adjusted firm size, $x_{t+1} \propto L_{t+1}/\tilde{N}_t^{\eta}$. The transmission of changes in the labor income tax rate, τ_t^l, to aggregate corporate investment operates through two channels: (i) changes in τ_t^l directly affect labor supply as intratemporal disturbances to the consumption-leisure trade-off; and (ii) equilibrium dynamics in the labor input drives entry in the corporate sector, thus determining the number of active firms. The implied dynamics in the labor input per active firm acts then as a disturbance to the intertemporal allocation of R&D investment.

Intertemporal tax disturbances. Next, we study how variation over time in tax rates alters the intertemporal allocation of R&D investment. By timing R&D expenditures, the corporate sector accomplishes intertemporal shifting of tax burden. Corporate R&D is tax deductible, such that the intertemporal allocation of R&D investment effectively alters the time path of taxable corporate income.

To this goal, we consider the rate of return to incumbents (RRI) investment and the rate of return to entrants (RRE) investment. We interpret RRI and RRE as investment schedules as represented in the $\left(i_t, r_{t+1}^a\right)$ space, where $i_t \equiv I_t/Z_{t-1}$ is the current R&D investment rate and r_{t+1}^a is the rate of return to corporate equity one period ahead. The intersection of RRE and RRI schedules describes the investment decision of the private sector as implied by no arbitrage. To sharpen intuition, we rely on perfect foresight and so abstract from uncertainty about the future path of tax rates. (See Appendix B.3 for details on the derivation of the RRI and RRE schedules.)

In symmetric equilibrium, the household's intertemporal condition for equity in (3.7) jointly with the intertemporal condition for R&D investment in (3.23), yields the RRI investment schedule:

$$r^a_{t+1} = \frac{\left(1-\tau^v_t\right)\left(1-\tau^d_{t+1}\right)\left(1-\tau^\pi_{t+1}\right) - \left(1-\tau^v_{t+1}\right)\left(1-\tau^d_t\right)\left(1-\tau^\pi_t\right)}{\left(1-\tau^d_t\right)\left(1-\tau^\pi_t\right)} +$$

$$+ \frac{\left(1-\tau^v_t\right)\left(1-\tau^d_{t+1}\right)\left(1-\tau^\pi_{t+1}\right)}{\left(1-\tau^d_t\right)\left(1-\tau^\pi_t\right)}\left(\frac{1-\theta}{\theta}\right)\alpha x_{t+1}. \tag{3.24}$$

Note that the RRI investment schedule in (3.24) is a flat line in the (i_t, r^a_{t+1}) space. This reflects the bang-bang property of the investment problem at the individual firm-level. At the aggregate level, the RRI schedule represents an indifference condition, that jointly with the RRE schedule below, describes the trade-off driving the intertemporal allocation of R&D investment in the corporate sector.

In symmetric equilibrium, the expression for the after-tax rate of return to equity in (3.4) jointly with the free-entry condition $V_t = \nu X_t$ yields the RRE investment schedule:

$$r^a_{t+1} = \underbrace{\left(1-\tau^d_{t+1}\right)\left(1-\tau^\pi_{t+1}\right)\left[\frac{\left(\frac{1-\theta}{\theta}\right)x_{t+1} - \phi - i_{t+1}}{\nu x_t}\right](1+i_t) +}_{\text{dividend-price ratio channel}}$$

$$+ \underbrace{\left(1-\tau^v_{t+1}\right)\left[\frac{x_{t+1}\left(1+i_t\right)}{x_t} - 1\right]}_{\text{capital gains channel}}. \tag{3.25}$$

Note that the RRE schedule in (3.25) is an upward-sloping line in the (i_t, r^a_{t+1}) space. Higher rates of return to corporate equity next period are associated to higher rates of investment in R&D today. Such a positive relationship materialize through two channels. Everything else equal, a higher investment rate today is associated to

(i) a higher dividend-price ratio tomorrow, and to (ii) an appreciation of the market value of the corporate sector.

Explaining the effects of intertemporal disturbances in tax rates hinges on understanding if, how, and to what extent the RRI and the RRE schedules shift in response to tax changes. Next, we discuss a few experiments in tax policy that illustrate the transmission mechanisms embodied in the model. First, we stress that *current* tax rates only enter the RRI schedule in equation (3.24). Thus, changes in current tax rates, keeping fixed future ones, affect the R&D investment rate today by shifting the RRI investment schedule either upward or downward. As an example, let us consider a reduction in either the dividend tax, or the corporate tax, or both, while keeping future tax rates fixed at their current values. In this scenario, the RRI schedule shifts downward, whereas the RRE schedule remains unchanged. As a result, the current investment rate unambiguously declines, implying a lower return to corporate equity tomorrow.

Second, changes in *future* tax rates disturb both the RRI and RRE investment schedules. Let us consider next a reduction in either next period dividend tax, or corporate tax, or both, while keeping current tax rates unchanged. The RRI schedule shifts upward. Holding the RRE fixed, this upward shift in the RRI schedule would imply an unambiguous increase in the current investment rate. However, the RRE moves to the left, such that the overall effect is in principle ambiguous.

Third, we consider changes in current and next period tax rates on capital gains. A reduction in the current tax rate on capital gains, relative to tomorrow's value, shifts the RRI schedule upward while leaving the RRE schedule unchanged. As a result, the current investment rate unambiguously raises implying a higher return to corporate equity. By contrast, a reduction in next period tax rate relative to its current value unambiguously reduces the current investment rate. Holding the RRE fixed, the downward shift in the RRI schedule implies an unambiguous reduction in the current investment rate. This effect is further amplified by the leftward shift of the RRE investment schedule.

3.4.4 Determinants of Growth

To understand the role of tax policy for the determination of long-term rates of economic growth, we use the equations that describe the steady state of the model. In the steady state with constant tax rates (and $\sigma_t = 1$, for all $t \geqslant 0$), the steady-state growth rate of output per capita is determined by a low-dimensional system, that links the quality-adjusted firm size in the corporate sector, $x_t \equiv X_t/Z_{t-1}$, to the steady-state gross growth rate of quality improvement, $z_t \equiv Z_t/Z_{t-1}$. Along the balanced growth path (BGP), the gross growth rate of quality z_t and firm size x_t are constant. (Henceforth, we omit time subscripts unless needed for clarity.)

The system consists of a product innovation (PI) locus that captures the incentives to firms' entry in the corporate sector:

$$z = \beta\left(1-\delta\right)\left[\left(1-\tau^{d}\right)\left(1-\tau^{\pi}\right)\left(\frac{1-\theta}{\theta\nu}-\frac{z-1+\phi}{\nu x}\right)z+\left(1-\tau^{v}\right)\left(z-1\right)+1\right]. \tag{3.26}$$

And of a quality innovation (QI) locus that captures the incentives to investment in quality improvement of incumbent firms in the corporate sector:

$$z = \beta\left(1-\delta\right)\left[\left(1-\tau^{v}\right)\left(\frac{1-\theta}{\theta}\right)\alpha x+1\right]. \tag{3.27}$$

The PI locus in (3.26) describes the steady-state quality-adjusted R&D investment rate $I_t/Z_{t-1} = z_t - 1$ that equalizes the rate of return to entry to the rate of return to quality investment, given the value of x that both entrants and incumbents expect to achieve in equilibrium. The QI locus in (3.27) describes instead the steady-state investment rate that incumbent firms generate given the quality-adjusted firm size, x, that they expect to achieve in equilibrium. (See Appendix B.3 for details on the derivation of the PI and QI locus.) The steady state is the intersection of these two locus in the (x, z) space. Figure 3.1 illustrates the determination of the steady state of the model based on our baseline parametrization, which we discuss at length in Section 3.5.1 below.

Few remarks are in order. First, the corporate tax rate does not enter the QI locus as the R&D expensibility parameter is set to $\sigma_t = 1$ at all times. This approach replicates in the model the full expensibility of R&D investment granted by the U.S. tax code to incorporated firms. Second, the dividend tax rate does not enter the QI locus as corporate investment is financed by retained earnings instead of equity. This accords to the "new view" of corporate finance (see Auerbach, 2002).

Existence and stability of the steady state require an intercept condition that the PI curve starts out below the QI curve and a slope condition that the PI curve is steeper than the QI curve. Together they imply that a stable steady state (x^*, z^*) exists with the PI curve cutting the QI curve from below. In order to see the stability of such steady state, notice that if the system starts at a slightly higher $x > x^*$, then the return to product innovation is higher than the return to quality innovation (since the PI curve is above the QI line to the immediate right of the intersection). This spurs entry and increases the number of firms. Since x is inversely related to the number of firms, x then falls forcing the system to revert back to steady-state value x^*. Note that because the QI locus is a line and PI is an inverted parabola, there will be another intersection at higher values of x and z. Yet, such steady state is unstable. The baseline parameter values in Section 3.5.1 yield local stability of equilibrium dynamics around the stable steady-state.

In the model, the steady-state growth rate of quality improvement, z^*, is the only driver of aggregate TFP and real GDP growth. This result is due to the presence of fixed operating costs. An ever expanding number of products puts pressure on

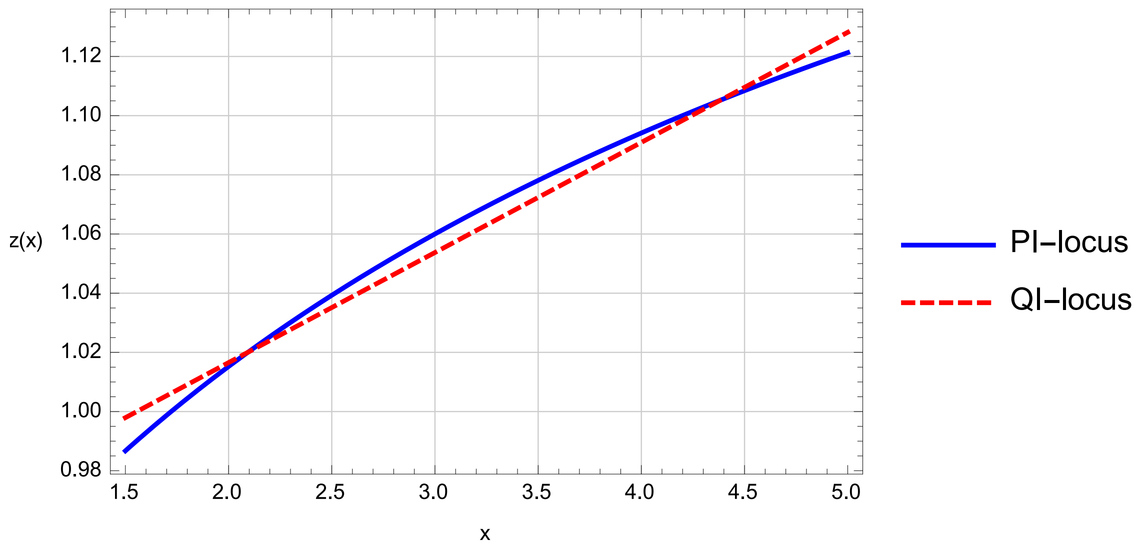

FIGURE 3.1: Determination of Steady-State Growth Rate of Quality Improvement

Notes: On the horizontal axis, $x_t \equiv X_t/Z_{t-1}$ is the quality-adjusted firm size, whereas on the vertical axis, $z_t \equiv Z_t/Z_{t-1}$ is the gross growth rate of quality improvement. The PI locus (solid line) describes the gross growth rate of quality improvement, z_t, needed to equalize the rate of return to entry to the rate of return to quality-improving investment, given the value of x_t that both entrants and incumbents expect to achieve in equilibrium. The QI locus (dashed line) describes the gross growth rate of quality improvement, z_t, that incumbent firms generate given the quality-adjusted firm size, x_t, that they expect to achieve in equilibrium. See Section 3.5.1 for further details on the baseline parametrization of the model.

the economy's aggregate resources by duplicating fixed costs, which in turn makes firm's entry, and so expanding-variety innovation, irrelevant for long-run productivity growth. The irrelevance of product innovation for long-term rates of economic growth has important implications for tax policy.

In the system (3.26)-(3.27), the corporate income tax, τ^{π}, and the individual income tax on dividends, τ^{d}, and capital gains, τ^{v}, jointly determine the steady-state growth rate of quality improvements and thereby of output per capita. In the model, tax rates on corporate income and individual asset income affect equilibrium behavior through two channels: (i) tax rates change budget sets; (ii) tax rates change entry and investment decisions by distorting intertemporal first-order conditions. Yet, we emphasize that the steady-state growth effects of corporate and asset income taxation remain even if tax revenues are lump-sum rebated to the household. This happens because *constant* tax rates affect steady-state relative rates of return to entrants' and incumbents' investment and thereby the "great ratio" of the theory, quality-adjusted firm size, leading then to substitution effects. Tax rates on individual asset income play a key role in corporate investment decisions.

Next, we emphasize that neither the consumption tax rate nor the labor income tax rate enter the determination of the steady-state rate of quality improvement, z^*, in the system (3.26)-(3.27). Explaining why this happens is key to understanding the transmission mechanism of tax policy embodied in the model. The PI and QI curves capture the insight that firms' entry and R&D investment decisions by incumbent firms do not directly respond to changes in consumption and labor income tax rates, but only indirectly through changes in quality-adjusted firm size. A permanent change in either τ^c or τ^l, or both, affects the equilibrium labor input, and thereby the aggregate demand for intermediate goods. These market-size effects are nevertheless sterilized in the long-run by net entry/exit of firms. To see this, (1) fix the number of firms, then a change in either tax rate affects the quality-adjusted firm's size, x, and thereby incentives to quality-improving innovation. Everything else equal, this would have steady-state growth effects. (2) Now, let the mass of firms vary as in free-entry equilibrium; as the profitability of incumbent firms varies, the mass of firms endogenously adjusts (net entry/exit) to bring the economy back to the initial steady-state level of firm size, x^*. As a result, the adjustment process through firms' entry fully sterilizes the long-run growth effects of the initial tax change.

3.5 Quantitative Implications for the U.S. Economy

In this section, we study the quantitative predictions of the model. Specifically, we feed the U.S. post-war fiscal policy along with empirical estimates of policy expectations into the model and compute the equilibrium. We implement two types of policy analysis: (i) analysis of long-run effects of tax changes, through steady-state comparisons; and (ii) analysis of short-run effects of tax changes, through computation of approximate equilibrium dynamics in the neighborhood of the steady state, with no shocks to either government spending or tax rates. As a first step, we next choose parameter values, such that the model economy is consistent with salient features of the post-war U.S. economy. (See Appendix B.3 for the list of equilibrium conditions used to compute the approximate equilibrium of the model and a discussion of the solution method.)

3.5.1 Model Parametrization

We now turn to the parametrization of the model. Each time period is taken to represent a year. As for the calibration strategy, we exogenously set the value of a subset of parameters based on previous work and micro data, whereas we calibrate the rest of parameters to match specific moments in U.S. data. While none of the parameters has a one-to-one relationship to a moment, we can provide a heuristic description of identification.

Exogenously Set Parameters

Next, we discuss parameter values that are exogenously set.

Congestion of labor services in production. The reduced-form aggregate production function of the final good (gross output) reduces to:

$$Y_t = \tilde{N}_{t-1}^{1-(1-\theta)\eta} X_t^{\theta} \left(Z_{t-1} L_t\right)^{1-\theta}, \tag{3.28}$$

where the parameter $0 \leqslant \eta \leqslant 1$ captures the degree of congestion of labor services across intermediate goods. For $\eta = 0$ there is no congestion as labor services can be shared across intermediate goods with no productivity loss. For $\eta = 1$ there is instead full congestion. In the United States, population growth averaged 1.2 percent per year over the period 1977-2013, and the number of firms has grown at approximately 1.1 percent per year on average over the same time period. Importantly, these two figures are not statistically different from each other, which suggests that population and the number of firms indeed move in lockstep in the United States. Thus, we set $\eta = 1$. Data on the population of active firms in the U.S. business sector is from the Business Dynamics Statistics (BDS) dataset produced by the Census and available at `http://www.census.gov/ces/dataproducts/bds/index.html`.

Arguably, the calibration of the congestion parameter, and thereby the implied social return to variety, represents a challenging task. Hard evidence backing up a specific parameter value is scarce and often open to criticism. To address this concern, we check the sensitivity of our results to an alternative parametrization with partial congestion, based on a value of $\eta = 0.75$—labor congestion of 75 percent.

Government spending and taxes. We set $\bar{g}$ equal to 20.8 percent so that the mean of the government spending to GDP ratio in the model matches that in post-war data for 1946-2014. In the model, taxes are levied on (i) individual income, which consists of labor income, dividends of Schedule C corporations distributed to their owners, and capital gains on equity shares of the corporate sector, (ii) corporate income, which consists of profits of Schedule C corporations, and (iii) consumption expenditures. For the taxes levied on individual income, we set $\bar{\tau}^l$ equal to 20.6 percent to match the average labor income tax rate (ALITR) in the data for 1946-2014; $\bar{\tau}^d$ equal to 39.5 percent to match the average marginal dividend income tax rate (AMDITR) in the data for 1946-2003; and $\bar{\tau}^v$ equal to 17 percent to match the average capital gains tax rate (ACGTR) in the data for 1954-2013. For the tax levied on corporate profits, we set $\bar{\tau}^\pi$ equal to 32 percent to match the average corporate income tax rate (ACITR) in the data for 1946-2014. In the U.S. tax code, R&D expenditure is fully deductible from taxable corporate income so we set $\sigma_t = 1$ at all times. For the consumption tax, we set $\bar{\tau}^c$ equal to 8.2 percent to match the average consumption tax rate (ACTR) in the data for 1946-2014. The parameter estimates that govern the persistence of the deviations of the fiscal instruments from the long-run deterministic trends are reported in Table B.1.

Calibrated Parameters

Next, we discuss parameter values that are calibrated to targeted moments of U.S. data.

Preferences. Using data from the Current Population Survey (CPS), McGrattan and Prescott (2013) find that total hours of work relative to the working-age population averaged 1,442 hours per year in United States. If discretionary time per week is 100 hours, then the fraction of time spent at work is 0.277. Given our specification of preferences,

$$u(c_t, l_t) = \ln c_t - \gamma \frac{l_t^{1+\vartheta}}{1+\vartheta}, \tag{3.29}$$

we set γ equal to 9.33 to get the same predicted fraction of time spent at work for the model. Also, we set $\vartheta = 1$ so that the Frisch elasticity of labor supply equals one (see Chetty et al., 2012). In addition, we set the discount factor $\beta = 0.98$, so that in the model the risk-free interest rate r_t^b along the balanced growth path (BGP) is 4 percent, consistent with recent findings by Gomme et al. (2011).

Technology. The value of the parameter θ uniquely pins down the markup at $1/\theta$. The available evidence for the United States provides estimates of markups in value added data ranging from 1.1 by Basu and Fernald (1997) to 1.2 by Bils and Klenow (2004). Instead of settling on one specific value for the markup, we report results for two alternative economies featuring a price markup of 10 and 20 percent. We set then θ equal to 0.83 for a 20% markup and to 0.91 for a 10% price markup.

The firm's private return to quality improvement α is set equal to 0.31, so that along the BGP the R&D expenditure to GDP ratio in the model matches the average R&D-to-GDP ratio of 2.6 percent in the data for the period 1996-2012. Data on R&D expenditure as percent of GDP are from the World Development Indicators (WDI) produced by the World Bank and available at `http://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS`.

Firms' exit. We set the death rate of the firm to $\delta = 6.18$ percent such that the firm's exit probability in the model matches the mean of firms' exit rates in the data for 1977-2013, conditional on surviving for the first five years. Specifically, we calculate the firm's death rate as the number of firm deaths in the current period divided by the number of active firms in the previous period. All establishments owned by the firm must exit to be considered a firm death. Data on the population of active firms and on the number of firms' deaths in the United States are from the BDS dataset. In addition to the relatively high firms' death rate parametrization of 6.18 percent, we also experiment with $\delta = 3.94$ percent, which is the exit rate for mature firms of 25 years of age and older in the BDS dataset.

Entry and fixed operating costs. We finally set ϕ to 0.15 and ν to 0.54, such that the model matches the average growth rate of real GDP per capita of 2 percent in the data for the period 1948-2014, and the average labor share of GDP of 0.653 for the period 1948-2013 based on Koh et al. (2016).

Parameter Identification

The analytical tractability of the model BGP allows for a heuristic description of parameter identification. As standard in dynamic equilibrium models, none of the parameters has a one-to-one relationship to a specific moment. Yet, the cross-equation restrictions implied by the theory highlight key relationships between model parameters and targeted moments.

We consider the non-stochastic steady state of the model with constant tax rates. Tax rates along the BGP are calibrated to match the corresponding average values in the United States. Given our specification of preferences, the steady-state version of the household's intertemporal condition for bond holdings in (3.6) yields:

$$z_t = \beta R_t^b, \tag{3.30}$$

where $z_t \equiv Z_t/Z_{t-1}$ is the gross growth rate of quality improvement along the BGP, that is incidentally the steady-state growth rate of consumption. Given a target of 2% for real GDP growth and 4% for the risk-free interest rate, the relationship in (3.30) yields the calibrated value of $\beta = 1.02/1.04 \approx 0.98$. Recall that the pricing equation of the intermediate producers in (3.17) yields the unit price $p_t = 1/\theta$ for all $t \geqslant 0$. A target mark-up of 20% implies then the calibrated value of $\theta = 1/1.2 \approx 0.83$.

Notice that the production technology in (3.9) and price-taking behavior in the final good sector implies a constant labor share of gross output $w_t L_t / Y_t = 1 - \theta$. Next, we use the aggregate resource constraint $Y_t = \mathscr{Y}_t + \mathscr{Q}_t$ to derive an expression for the GDP-to-output ratio, $\mathscr{Y}_t/Y_t = 1 - \theta^2(1 + \phi/x)$, such that the labor share of GDP reduces to:

$$\frac{w_t L_t}{\mathscr{Y}_t} \equiv \frac{w_t L_t}{Y_t}\left(\frac{1}{\mathscr{Y}_t/Y_t}\right) = \frac{1-\theta}{1-\theta^2\left(1+\phi/x_t\right)}. \tag{3.31}$$

Few remarks are in order. First, the value of the parameter θ is uniquely pinned down at 0.83 by the 20% target for the price mark-up. Second, along the BGP, quality-adjusted firm size x_t is determined by the PI and QI locus in (3.26) and (3.27), respectively, jointly with the steady-state growth rate of quality improvement, z_t. Holding x_t fixed, there exists then a one-to-one relationship between the parameter governing the extent of fixed operating costs, ϕ, and the labor share of GDP. Notice that ϕ enters the expression for the PI locus as well, such that x_t is an implicit function of ϕ alongside other parameters of the model. Yet, we stress that though different parametrizations can produce the same numerical value for quality-adjusted firm size, x_t, different calibrations of ϕ imply drastically different implications for the labor share of GDP in the model. This argument suggests that the observed labor share of GDP indeed has relevant identifying information.

In the model, the R&D-to-GDP ratio is related to the labor share of GDP in (3.31) through a simple relationship:

$$\frac{\text{R\&D}_t}{\mathscr{Y}_t} = \frac{\theta^2(z_t - 1)/x_t}{1 - \theta^2(1 + \phi/x_t)} = \frac{w_t L_t}{\mathscr{Y}_t}\left(\frac{\theta^2}{1-\theta}\right)\frac{z_t - 1}{x_t}. \tag{3.32}$$

Given our targets of 65.3% for the labor share of GDP, and of 2% for real GDP growth, the expression in (3.32) restricts x_t. As a result, the remaining free parameters entering the PI and QI locus, (ϕ, ν, α), need to be jointly calibrated to reproduce the three targeted moments for the labor share of GDP, the R&D-to-GDP ratio, and the growth rate of real GDP.

Next, we highlight that the value of the labor input does not enter any of the steady-state relationships above. This feature of the equilibrium represents a cross-equation exclusion restriction, that reflects the sterilization of market-size effects along the BGP: Rates of return to firms' entry and incumbents' quality-improving innovation are independent of equilibrium labor. Yet, the parameters determining the BGP restrict the calibrated value of the steady-state labor input. This block recursive structure allows us to calibrate the economy to the targeted moments for the risk-free interest rate, the labor share of GDP, R&D-to-GDP ratio, and the growth rate of real GDP, independently of the labor input. Then, given the values for the exogenously set and calibrated parameters, the target of 0.277 for time spent at work implies the calibrated value for the disutility of work parameter of $\gamma = 9.33$.

Finally, we discuss identification of the parameter η governing congestion of labor services into the production of gross output. To this goal, we consider the equilibrium relationship $x_{t+1} = \theta^{\frac{2}{1-\theta}} L_{t+1}/\tilde{N}_t{}^{\eta}$ to derive an expression for the number of firms per capita (population size is normalized to one):

$$N_t^{\eta} = \frac{\theta^{\frac{2}{1-\theta}}}{(1-\delta)^{\eta}} \left(\frac{L_{t+1}}{x_{t+1}}\right). \tag{3.33}$$

The expression in (3.33) delivers a revealing cross-equation exclusion restriction implied by the equilibrium of the model. On the right-hand side of (3.33), the parameters θ and δ are uniquely pinned down by our targets for the price mark-up and firms' exit probability. In addition, the targeted value for the labor input and the implied steady-state value for quality-adjusted firm size are both determined independently of the equilibrium relationship in (3.33). There exists, then, a one-to-one relationship between the congestion parameter η and the number of firms per capita. The equilibrium of the model suggests that statistics on the number of firms per capita, and alike, indeed contain relevant identifying information for calibrating the congestion parameter.

In BDS data for 1977-2013, the ratio of civilian noninstitutional population (16 years of age and older) to the total number of firms in the U.S. business sector is approximately 45. This figure translates into a firms-to-population ratio of 0.02. In the baseline parametrization based on full congestion with $\eta = 1$, the model delivers a firms-to-population ratio of 0.016, which is strikingly close to the data for being an untargeted moment. If one restricts attention to firms of 5 years of age and older, instead, the ratio of population to the number of firms in that age group is approximately 77. This figure implies a firms-to-population ratio of 0.013, that can be exactly matched by setting the congestion parameter to 0.95. Furthermore, if we only consider mature firms of 25 years of age and older, then the ratio of population to the number of firms in that age group is 299. This figure implies a firms-to-population ratio of 0.003 that can be matched with a congestion parameter of roughly 0.75.

3.5.2 Growth Effects of Income Taxation

We now turn to investigate the quantitative effects of unanticipated and *permanent* changes in tax rates. Specifically, we compare the steady states of the model before and after the change in a specific tax rate, while keeping the remaining tax rates fixed at their steady-state values. In each experiment, the government budget constraint is balanced with the required change in lump-sum transfers.

We consider steady-state responses of real GDP/TFP growth and the R&D-to-GDP ratio to a 1 percentage point (pp) permanent cut in tax rates. To gauge the magnitude of these effects, we consider numerical solutions for the shifts in the equilibrium steady-state growth rates arising from small perturbations in each tax rate.

We next discuss two key predictions of the model for the long-run transmission mechanism of tax changes. First, permanent changes in the tax rate on consumption expenditures and on labor income have no effect on either the long-run growth rate of TFP or the level of the R&D-to-GDP ratio. This neutrality result stems from the interaction of firms' entry and quality-improving innovation. Changes in labor and consumption tax rates propagate through the economy by changing the scale of economic activity. Market-size effects are irrelevant for the long-term incentives to quality-improving innovation, and thereby neutral in terms of long-term rates of TFP and real GDP growth.

Second, permanent changes in tax rates on individual asset income (dividends and capital gains) and corporate income have, instead, a quantitatively large impact on aggregate TFP growth. The magnitude of this effect is sensitive to the parametrization of the firm's exit probability and of the price markup. We report then results for alternative parametrizations: Table B.2 shows results for the economy with a price markup of 20 percent, whereas Table B.3 shows results based on a price markup of 10 percent. Panel A of each table considers a high exit probability of 6.18 percent, which is the exit rate of firms of 5 years of age and older in the U.S. business sector. Panel B of each table considers a low exit probability of 3.94 percent, which corresponds to the exit rate of firms of 25 years of age and older.

20% price markup. The quantitative effects of a dividend and of a corporate tax cut have the same sign and are comparable in magnitude. Specifically, for the high-exit economy, a 1 pp cut in either tax rate halves the steady-state growth rate of the economy from 2% to approximately 1%. For the low-exit economy, instead, an equally-sized tax cut reduces growth by roughly 0.6 percentage points. By contrast, a 1 pp cut in the capital gains tax raises steady-state growth by nearly 0.6 percentage points in the high-exit economy, and by 0.2 percentage points in the low-exit economy. Overall, these are sizable effects.

The sensitivity of the growth effects of income taxation to the value of the firm's exit probability hinges on the following insight. Product quality is an asset that generates future income and product. The capitalized value of this asset depends on the total income expected to be realized over its economic life span and the market discount rate applied to this stream of generated income. A higher probability of firm's death/exit lowers the expected economic life span of its product, which implies a higher effective discount rate applied to the future income generated by the firm. Everything else equal, a higher discount rate reduces then the capitalized value of product quality, such that a tax cut of a given size has a disproportionally large impact on the total asset value of the firm.

10% price markup. The quantitative effects of a dividend and of a corporate tax cut have again the same sign and are comparable in magnitude. For the high-exit economy, a 1 pp cut in either tax rate reduces the steady-state growth rate of the economy by approximately 0.5 percentage points. For the low-exit economy, an equally-sized tax cut reduces growth by roughly 0.3 percentage points. By contrast, a 1 pp cut in the capital gains tax raises steady-state growth by nearly 0.3 percentage points in the high-exit economy, and by 0.15 percentage points in the low-exit economy. Notice that reducing the price markup from 20 to 10 percent nearly halves the steady-state responses to tax cuts across the board. The extent of market power is indeed a key conditioning variable for understanding the transmission of asset and corporate income taxation to long-term growth rates of TFP.

Shutting down firms' entry. To understand the role played by firms' entry, we next consider a variant of the model in which the number of firms is held fixed, and thus by construction invariant to changes in the economic environment.

To shut down firms' entry, we proceed in two steps: (i) we eliminate from the model the free-entry condition $V_t = \nu X_t$ ("firm creation technology"); and (ii) we make the incumbent firms live forever, such that $\delta = 0$ at all times. This eliminates two parameters, (δ, ν), from the model. (Notice that this formulation of the model can be viewed as the limit case of a large enough sunk entry cost, which effectively deters entry in the corporate sector.) Also, we re-calibrate the parameters $\alpha = 0.12$ and $\gamma = 8.15$ to match the baseline targets of 2% for real GDP growth and 0.277 for the time spent at work, respectively.

In Appendix B.4, Table C.1 shows the steady-state responses to tax cuts in the economy with a fixed number of firms. An immediate consequence of firms' entry shutdown is that the model now displays market-size effects in the long-run: steady-state growth depends on the level of the labor input. As a result, changes in labor income tax rates affect the steady-state growth rate of quality improvement, and thereby aggregate TFP and real GDP growth.

3.5.3 Level Effects of Income Taxation

We now turn to study the dynamic adjustment of the economy in response to unanticipated and *temporary* changes in tax rates. To this goal, we rely on impulse response functions (IRFs) to tax shocks as they illustrate the propagation mechanisms embodied in the model. Specifically, we study the dynamic effects of a temporary change in a specific tax rate, while keeping the other tax rates fixed at their baseline steady-state values, and the government budget constraint balanced at all times through lump-sum transfers. We consider a 1 pp cut in a given tax rate, which is (in expectation) known to last for several periods. In the model, the expectations about the persistence of tax shocks are disciplined by reduced-form estimates based on autoregressive processes fitted to U.S. tax data. The dynamic responses to a tax shock are computed as deviation from the steady-state *trend* for growing variables and from the steady-state *level* for stationary variables.

Dynamic responses to tax cuts. Figures B.2 through B.5 show IRFs to individual and corporate income tax cuts. Two main quantitative results stand out: (i) temporary tax cuts have a sizable permanent effect on the level of real GDP per capita, labor productivity, and TFP; and (ii) the model displays substantial internal propagation.

In response to a 1 pp cut in the labor tax rate, the labor input raises on impact, it then reverts back to the initial steady-state level mimicking the dynamics of the tax shock. The temporary expansion in equilibrium labor feeds into a temporary expansion in the aggregate demand for intermediate goods production. These transitional market-size effects stimulate aggregate R&D investment in the corporate sector and thereby spur a temporary acceleration of labor productivity and TFP growth. As a result, real GDP sluggishly raises during the transition dynamics and settles on an approximately 1.6 percent higher level relative to the previous trend. During the transition dynamics, firms' entry rate falls below the steady-state level, such that the number of firms in the corporate sector temporarily declines and slowly reverts back to the initial steady-state level. The response of the number of firms is U-shaped reflecting the internal propagation embodied in the model.

Next, we discuss the dynamic responses to the dividend and corporate tax cut. We lump together the discussion as the responses are indeed comparable both in terms of transmission mechanism and of sign and size of the overall effect on aggregate quantities. The adjustment dynamics in response to the dividend and corporate tax cut is rather complex, reflecting the dynamics of the tax shock itself. In the data, dividend and corporate tax shocks follow third-order AR processes, such that the reversion to the initial steady-state value need not be monotonic. In response to a 1 pp cut in the tax rate, aggregate R&D investment temporarily declines below the long-run level, leading to a temporary deceleration in labor productivity and TFP growth. Such a deceleration in aggregate productivity leaves a sizable permanent effect on the level of real GDP, that settles on an approximately 5 percent lower level relative to previous trend. By contrast, in response to an equally-sized cut in the tax rate on capital gains, the economy experiences a temporary acceleration in aggregate productivity growth, that translates into a roughly 5 percent higher level of real GDP relative to previous trend.

Overall, the IRF analysis points to a quantitatively important effect of income taxation on aggregate innovation and thereby on aggregate productivity and real GDP per capita.

Robustness. In Appendix B.4, Figures C.1-C.12 show additional IRFs based on several parametrizations of the model (higher firm's exit probability and partial congestion of labor services in production) and for a variant of the model with a fixed number of firms.

3.5.4 Sources of Aggregate Productivity Growth

We now turn to quantify the role played by firms' entry and incumbents' quality improvement in determining the dynamics of aggregate productivity growth. Specifically, we ask how much of the variation in productivity growth can be attributed to variation in the number of firms/products as opposed to variation in product quality. To this goal, we consider the expression for TFP implied by the model:

$$A_t \propto Z_t N_t^{1-\eta}, \tag{3.34}$$

where A_t denotes current TFP, Z_t and N_t are respectively the stock of knowledge and number of firms inherited from the previous period, and η parametrizes the degree of congestion of labor services in production. In the model, aggregate TFP is proportional to a composite of number of products and product quality. Variation over time of these two equilibrium quantities, and their dynamic interactions, determine the overall variation in TFP growth.

Note that under full congestion, the number of firms drops out of the expression for TFP in (3.34). As a result, all variation in TFP is due to the aggregate dynamics in product quality. Next, we provide results based on variance decompositions under partial congestion of labor services. We consider *unconditional* variance decompositions based on simulated time-series from the economy where all tax shocks are turned on.

Aggregate TFP growth. Using the expression in (3.34), we next consider growth rates:

$$d\ln A_t = d\ln Z_t + (1-\eta) d\ln N_t, \tag{3.35}$$

where $d\ln A_t \equiv \ln A_t - \ln A_{t-1}$ indicates the percentage growth rate in TFP. Then, we apply the textbook variance/covariance decomposition formula to equation (3.35), which yields

$$\mathrm{Var}(d\ln A_t) = \mathrm{Var}(d\ln Z_t) + (1-\eta)^2\mathrm{Var}(d\ln N_t) + 2(1-\eta)\mathrm{Cov}(d\ln Z_t, d\ln N_t).$$

Using such an additive decomposition, we measure the relative contribution of product quality and number of products as follows:

$$\textbf{share}^{\mathrm{TFP}}_{\mathrm{quality}} \equiv \frac{\mathrm{Var}(d\ln Z_t)}{\mathrm{Var}(d\ln Z_t) + (1-\eta)^2\mathrm{Var}(d\ln N_t)}; \tag{3.36}$$

$$\textbf{share}^{\mathrm{TFP}}_{\mathrm{entry}} \equiv \frac{(1-\eta)^2\mathrm{Var}(d\ln N_t)}{\mathrm{Var}(d\ln Z_t) + (1-\eta)^2\mathrm{Var}(d\ln N_t)}. \tag{3.37}$$

Table B.4 shows the results for the variance decomposition of TFP growth. Panel A reports the theoretical variances and covariances of TFP and its components. The unconditional variance of growth in product quality and in the number of firms raises as we reduce the degree of labor congestion in production. Specifically, the variance of product quality growth raises by 12.4 percent from the full congestion case to partial labor congestion of 75 percent. The variance of growth in the number of firms raises by approximately 25.6 percent. Yet, the unconditional variance of aggregate TFP declines as product quality and number of firms co-more more negatively as labor congestion decreases. The covariance between product quality growth and the growth in the number of firms raises in absolute terms by nearly 33 percent. Panel B shows the relative contribution of product quality and number of firms to TFP growth.

3.6 Evaluation of Tax Reforms

In this section, we quantitatively evaluate proposals for reforming the U.S. tax system. Each proposal aims at achieving a growth rate of real GDP per capita of 3 percent. Our approach to evaluating tax reforms consists of four steps. First, (i) we discipline the model by using the parameter values calibrated to match targeted moments in U.S. annual data. In doing so, we rely on the assumption that parameters are invariant to the tax reform. (ii) We explicitly set a 3% target for real GDP growth, that the tax reform is required to achieve to be viewed as successful. (iii) We restrict the range of values that some tax instruments can take, such that the reform proposal broadly mimicks tax reforms enacted in the United States in the near past. This restriction on tax rates arguably provides realism to the counterfactual analysis: If the reform proposal was already enacted in the near past, it may as well receive enough political support to be enacted in the near future. Finally, (iv) we keep the government spending-to-GDP ratio fixed at 21 percent and let transfer payments to the household sector adjust to balance the government budget.

3.6.1 Government Receipts and Expenditures Account

We now turn to the details of government outlays and revenues. In the model, the government budget constraint implies the receipts and expenditures account of the government sector:

$$\underbrace{\frac{G_t}{\mathrm{GDP}_t} + \frac{\Omega_t}{\mathrm{GDP}_t}}_{\text{expenditures}} = \tag{3.38}$$

$$\underbrace{\tau_t^c\left(\frac{C_t}{\mathrm{GDP}_t}\right) + \tau_t^l\left(\frac{w_t L_t}{\mathrm{GDP}_t}\right) + \tau_t^d\left(\frac{\tilde{D}_t}{\mathrm{GDP}_t}\right) + \tau_t^v\left(\frac{\Delta\tilde{\mathscr{V}}_t}{\mathrm{GDP}_t}\right) + \tau_t^\pi\left(\frac{\tilde{\Pi}_t}{\mathrm{GDP}_t}\right)}_{\text{tax receipts}}.$$

Expression (3.38) reminds us that tax receipts inherently depend on both tax rates and the tax base. And that the tax base consists of several sources of taxable income: labor income, $w_t L_t$, dividends, $\tilde{D}_t$, and capital gains, $\Delta\tilde{\mathscr{V}}_t$, in the household sector; and operating profits, $\tilde{\Pi}_t$, in the corporate sector. Hence, the quantitative impact of a given tax reform ultimately depends on both the mix of tax instruments, and the short- and long-term taxable income elasticities.

In implementing a tax reform proposal, we maintain the government spending-to-GDP ratio (GRATIO) fixed at $\bar{g} = 20.8$ percent, as in our baseline calibration in Section 3.5. Note that in the United States, the GRATIO has been fluctuating about a 21 percent level since the early-1980s, whereas average effective tax rates have experienced substantial variation over the same period. It would then seem plausible to keep the size of the government sector (as measured by the GRATIO) invariant to the specific tax reform implemented. Also, the implementation of the proposals forces transfers to bear all the adjustment needed to balance the government budget.

3.6.2 Flat Individual Income Tax

We stress that the tax reforms implemented in the model achieve by construction the 3% target for real GDP per capita growth in the long-run. In evaluating the impact of a tax reform proposal, then, we rely on two metrics. First, we look at the implied labor and profit income shares of GDP. Historically, the implications of tax policy for functional income distribution have been key to arguments either in support or against tax reform proposals. Second, we compute the implied share of private consumption in GDP as a simple measure of welfare gains/losses implied by the reform.

Tax Reform Act of 1986 revisited. The salient feature of the tax reform proposal is the simplification of the individual income tax. In this respect, the reform shares key features of the Tax Reform Act of 1986 (TRA86). The proposal consists of three components:

(i) Flat tax rate on individual income (earnings, dividends, and capital gains);

(ii) Keep the government spending-to-GDP ratio at 21 percent;

(iii) Adjust lump-sum transfers to balance the government budget.

We acknowledge that TRA86 was not designed to keep the size of the government sector fixed at the value of year 1986. However, the government spending-to-GDP ratio remained nearly constant at 21 percent over the 10-year period 1980-1990 around the reform.

Isogrowth tax frontier. The equilibrium of the model implies that the 3 percent target for real GDP growth is achieved by several combinations of individual and corporate income tax rates. These different combinations of tax rates form an *isogrowth tax frontier* (ITF).

In Figure B.6, panel A shows the ITF: All feasible combinations of individual income tax rates τ^y on the x-axis and corporate income tax rates τ^π on the y-axis, that achieve the 3% long-term growth target in real GDP per capita. The ITF is downward-sloping implying a trade-off between individual and corporate income taxation. Higher taxation of corporate income mandates lower taxation of individual income. Panel B through D show the share of private consumption in GDP and the labor and profit income shares of GDP along the ITF.

3.7 Conclusion

In this paper, we develop a quantitative theory of innovation-led growth. Prominent feature of the theory is the interplay between product and quality innovation: Entrant firms create new products whereas incumbent firms improve own existing products. Market structure is endogenous: firm size and number of firms are jointly determined in free entry equilibrium. We restrict the theory to fit annual data for the post-war U.S. economy. Furthermore, the model embodies key features of the U.S. government sector, such as an individual income (earnings, dividends, and capital gains) and corporate income tax, a consumption tax, and government purchases. The results indicate that endogenous technological progress and market structure are quantitatively important channels for the transmission of tax policy to aggregate productivity and real GDP growth.

4

Conclusion

This dissertation consists of two independent chapters. The conclusions of the first and second chapters are in section 3.7 and 2.7, respectively.

Appendix A

Appendices of Chapter 2

Appendix A.1 contains all the proofs. Appendix A.2 presents a micro-foundation for my innovation technology. Appendix A.5 contains auxiliary graphs, and appendix A.6 includes supplementary tables.

A.1 Proofs

This section contains the proofs of the lemmas and propositions in the text.

Proof of lemma 1: Differentiating (2.28) with respect to s and simplification yields

$$n'(s) = L\frac{\epsilon}{\beta}\Big(\frac{1-s}{s}\Big)^{\frac{1}{\epsilon-1}}\frac{-1}{s(\epsilon-(\epsilon-1)s)^2} < 0,$$

which proves that $n(s)$ is a decreasing bijection. $\square$

Proof of lemma 2: First, replace $\xi = \epsilon - (\epsilon - 1)s$ in the expression $s\frac{2-\xi}{\xi}$ and differentiate to arrive at:

$$\frac{(2-\epsilon)\epsilon + 2s(\epsilon-1)\epsilon - s^2(\epsilon-1)^2}{(\epsilon-(\epsilon-1)s)^2}.$$

For the ratio to be positive, we need the numerator to be positive. Supposing that $\epsilon \in (1, 2]$ such that $(\epsilon - 2)\epsilon > 0$, it is enough to have $2s(\epsilon - 1)\epsilon - s^2(\epsilon - 1)^2 > 0$, and simplifying the relation shows it is true:

$$0 < 2s(\epsilon - 1)\epsilon - s^2(\epsilon - 1)^2$$

$$s < \frac{2\epsilon}{\epsilon - 1},$$

but the RHS is obviously larger than 1 for $\epsilon \in (1, 2]$, and s being a share is less than 1. Hence, this relation is true and the proof is complete. $\square$

Proof of proposition 3: It is enough to show that $s\frac{2-\xi}{\xi}$ is decreasing in n. But as long as $\epsilon \in (1, 2]$, lemma 1 and 2 show that

$$\frac{\partial}{\partial n}\Big(s\frac{2-\xi}{\xi}\Big) = \frac{\partial}{\partial s}\Big(s\frac{2-\xi}{\xi}\Big)s'(n) < 0.$$

$\square$

Proof of proposition 4: The solution to the right hand side of (2.29) is stable if and only if $\frac{\dot{n}}{n}$ in the space of $(n, \frac{\dot{n}}{n})$ goes from positive to negative at its solution, or simply put, $\frac{\dot{n}}{n}$ is decreasing in n at its solution. But since the right hand side of (2.29) is decreasing in n, this condition holds if and only if the coefficient of $\frac{\dot{n}}{n}$ is positive that is $1 - \frac{1-\rho\gamma}{\alpha\psi\gamma} > 0$. Notice that at equilibrium where $\psi = 1$, this condition is simplified to $\gamma > \frac{1}{\alpha+\rho}$. $\square$

Proof of proposition 5: I discuss the case in which as the market share of large firms grows, R&D investment starts before the entrepreneurship, *i.e.*, $s_{\underline{z}} < s_e$. Notice that if the R&D investment starts first, at the $s_{\underline{z}}$ we have $z = 0$ and $\frac{\dot{n}}{n} = -\delta$. Thus, from (2.26) we have

$$\rho = \frac{\alpha}{1 - \rho\gamma}s\frac{\xi - 1}{\xi}.$$

Notice that the right hand side is an inverted-U function that starts and ends at zero as s goes over its domain $[0, 1]$. Thus, if α is not too small, the right hand side crosses the constant left hand side at two points between which we have $z > 0$. The smaller crossing point gives us the $s_{\underline{z}}$. Next, note that because $s_e \in (s_{\underline{z}}, s_{\overline{z}})$, at the $s_{\overline{z}}$ we have

$$0 = -(\rho + \delta) - \frac{\dot{n}}{n} + \frac{\alpha}{1 - \rho\gamma} s \frac{\xi - 1}{\xi},$$

where we know that $\frac{\dot{n}}{n} > -\delta$, and from the (2.29) we have

$$\frac{\dot{n}}{n} = -(\rho + \delta) + \Big(\frac{1}{1 - \rho\gamma} \frac{1}{n} s \frac{1}{\xi} - \phi\Big) \frac{n(1 - \rho\gamma)}{\gamma}.$$

Substituting the $\frac{\dot{n}}{n}$ from above into the previous equation and simplifying gives us

$$\Big(1 + \frac{\alpha\gamma}{1 - \rho\gamma}\Big) s \frac{1}{\xi} - \frac{\alpha\gamma}{1 - \rho\gamma} s = n\phi(1 - \rho\gamma).$$

I show that this equation has a unique solution which gives us $s_{\overline{z}}$: Notice that the right hand side is a decreasing function from ∞ to zero, and the left hand size starts at zero and ends at one, and is increasing over its range from zero to one. This is because for small values of $\frac{\alpha\gamma}{1-\rho\gamma}$ the function is convex increasing over its domain. However, for larger values of $\frac{\alpha\gamma}{1-\rho\gamma}$, the function has a U shape that starts from zero, goes into negative range, and then turns up and ends at one. Either way, it is guaranteed that there is a unique crossing point between the right hand side and the left hand side, which gives us the point $s_{\overline{z}}$. Note that the fact that $s_{\underline{z}} < s_{\overline{z}}$ immediately results from $-\delta < \frac{\dot{n}}{n}$ for $s_e < s$, and that $\rho = \frac{\alpha}{1-\rho\gamma} s \frac{\xi-1}{\xi}$ has two solutions. However, it is possible that the maximum point between $s_{\underline{z}}$ and $s_{\overline{z}}$ is below s_e, at s_e, or above s_e.

Next, I derive the condition for $s_e \in (s_{\underline{z}}, s_{\overline{z}})$. Note that for $s \geqslant s_e$ we have $\frac{\dot{n}}{n} \geqslant -\delta$. Hence, the equations

$$z = -(\rho + \delta) - \frac{\dot{n}}{n} + \frac{\alpha}{1 - \rho\gamma} s \frac{\xi - 1}{\xi}$$

$$\frac{\dot{n}}{n} = -(\rho + \delta) + \Big(\frac{1}{1 - \rho\gamma} \frac{1}{n} s \frac{1}{\xi} - \phi - \frac{1}{\alpha n} z\Big) \frac{n(1 - \rho\gamma)}{\gamma},$$

with $\frac{\dot{n}}{n} = -\delta$ and substituting out z gives us

$$-\delta = -(\rho + \delta) + \Big(\frac{1}{1-\rho\gamma}\frac{1}{n}s\frac{1}{\xi} - \phi - \frac{1}{\alpha n}\Big(- (\rho+\delta) + \delta + \frac{\alpha}{1-\rho\gamma}s\frac{\xi - 1}{\xi}\Big)\Big),$$

which after simplification becomes

$$s\frac{2-\xi}{\xi} = \rho(\gamma - \frac{1-\rho\gamma}{\alpha}) + n\phi(1-\rho\gamma).$$

Note that the left hand side is an increasing convex function from zero to one, and the right hand side is a decreasing convex function from infinity to $\rho(\gamma - \frac{1-\rho\gamma}{\alpha})$. Thus, as long as $\rho(\gamma - \frac{1-\rho\gamma}{\alpha}) < 1$, the above equation is guaranteed to have a unique solution that gives us s_e.

Briefly said, the conditions that give us $s_{\underline{z}}$, s_e, and $s_{\overline{z}}$ are respectively the following three equations:

$$\begin{aligned} \rho\frac{1-\rho\gamma}{\alpha} &= s\frac{\xi-1}{\xi} \\ n\phi(1-\rho\gamma) + \rho(\gamma - \frac{1-\rho\gamma}{\alpha}) &= s\frac{2-\xi}{\xi} \\ n\phi(1-\rho\gamma) &= \Big(1 + \frac{\alpha\gamma}{1-\rho\gamma}\Big)s\frac{1}{\xi} - \frac{\alpha\gamma}{1-\rho\gamma}s, \end{aligned}$$

It can be seen that an increase in α lowers $s_{\underline{z}}$, and increases $s_{\overline{z}}$, while we can adjust s_e in between $s_{\underline{z}}$ and $s_{\overline{z}}$ by putting an upper and lower bound on the value of γ.

Finally, notice that if there is an upper bound $\gamma < 1/\rho$ for the parameter that regulates the cost of creating a new product, then we need the condition $\frac{1-\rho\gamma}{\alpha\gamma} < 1$ for the steady-state solution to stable (this can thought of as a lower bound on γ, *i.e.*, $\frac{1}{\rho+\alpha} < \gamma$). In this case, it is not possible to have $s_e < s_{\underline{z}} < s_{\overline{z}}$. The reason is that as discussed above, the equation that would give us $s_{\underline{z}}$ and $s_{\overline{z}}$ is the last equation above. But as shown above, this equation only has one solution that is associated to $s_{\overline{z}}$. □

Proof of proposition 6: Consider the function $F(n) = \frac{\dot{n}}{n}|_{z=0} - \frac{\dot{n}}{n}|_{z>0}$. In order to show that $\frac{\dot{n}}{n}$ is more negative when $z > 0$, it is enough to show that the derivative of $\frac{dF(n)}{dn} > 0$. Below, I write the function $F(n)$:

$$
\begin{aligned}
F(n) &= \frac{s}{\gamma}\frac{1}{\xi} - \frac{1-\rho\gamma}{\alpha\gamma}\frac{\alpha\phi}{L}n + \frac{1}{1-\frac{1-\rho\gamma}{\alpha\gamma}}\frac{s}{\gamma}\frac{\xi-2}{\xi} + \frac{\frac{1-\rho\gamma}{\alpha\gamma}}{1-\frac{1-\rho\gamma}{\alpha\gamma}}\frac{\alpha\phi}{L}n \\
&= \frac{s}{\gamma}\frac{1}{\xi} + \frac{1}{1-\frac{1-\rho\gamma}{\alpha\gamma}}\frac{s}{\gamma}\frac{\xi-2}{\xi} + \left(\frac{1}{1-\frac{1-\rho\gamma}{\alpha\gamma}} - 1\right)\frac{1-\rho\gamma}{\alpha\gamma}\frac{\alpha\phi}{L}n.
\end{aligned}
$$

The part that contains n is already increasing, and it becomes steeper as $\frac{1-\rho\gamma}{\alpha\gamma}$ gets larger (closer to one). Also, $s\frac{\xi-2}{\xi}$ is decreasing in s and hence increasing in n. Thus, the condition $\frac{1-\rho\gamma}{\alpha\gamma}$ being large enough is sufficient to make the two functions $s\frac{\xi-2}{\xi}$ and n dominate $s\frac{1}{\xi}$ which is the only decreasing part in n. This is sufficient to make $F'(n) > 0$. □

Proof of lemma 7: Equation (2.28) shows that $\frac{n}{L}$ is a function of the $\{s; \beta, \epsilon\}$. Moreover, recall from lemma 1 that there is a decreasing bijection between s and n. Thus, equation (2.27) can be expressed as $s = s(\frac{n}{L}; \epsilon, \beta)$. Replacing for $s(\frac{n}{L}; \epsilon, \beta)$ in (2.29), then $\frac{\dot{n}}{n} = 0$ can be written as $F(\frac{n}{L}; \Omega) = 0$, where $\Omega = \{\rho, \delta, \gamma, \alpha, \epsilon, \phi, \beta\}$. Hence, the solution to n on the balanced growth path has the form of $n = Lf(\Omega)$. □

Proof of proposition 8: The equation for no arbitrage in product innovation (2.26) on the BGP and $s = s(\frac{n}{L}; \epsilon, \beta)$ yield $z = g\big(s(\frac{n}{L}; \epsilon, \beta); \Omega\big)$. But lemma 7 showed that $\frac{n}{L} = f(\Omega)$, and hence I can write $z = g(\Omega)$, and does not depend on L. □

A.2 Micro Foundation for Innovation Technology

Process Innovation Technology: one of the critical assumptions of the model is *learning by doing* in process innovation: engaging in innovative activity makes future innovations easier. To formulate this principle, I start with some simplifying assumptions. First, process innovation is performed by a pool of scientists, denoted by

L_s. The pool of scientists is a constant share of total population. Second, there is a lot of churning among the scientists such that their expected productivity is the same. Third, the rate of processes innovation by scientists in firm i depends on how productive the scientists were in the past (*i.e.* learning by doing). In particular, the expected innovation rate $\dot{Z}_i$ for each scientist hired from the pool of scientists is proportional to the average production between now and some time in the past. Thus, if the firm i hires L_{Z_i} scientists, its process innovation rate satisfies the following:

$$\dot{Z}_i \propto \left(\frac{\int_{j \in n_t} Z_{j,t}\, dj - \int_{j \in n_{t-\ell}} Z_{j,t-\ell}\, dj}{L_s} \right) L_{Z_i},$$

where ℓ is the length of time over which the learning took place. The fourth simplifying assumption is that learning is perpetual, which manifests in $\ell \to \infty$. Since learning by doing implies an exponential growth in technology of each firm (given that there was a positive technology investment in the past), the term $\int_{j \in n_{t-\ell}} Z_{j,t-\ell}\, dj \to 0$ as learning becomes perpetual, and hence we have

$$\dot{Z}_i \propto \left(\frac{\int_{j \in n} Z_j\, dj}{L_s} \right) L_{Z_i}.$$

Finally, I assume that $L_s > \int_{j \in n} Z_j\ dj$, such that there is no problem with the shortage of scientists (or high quality engineers) in the economy at any time. Moreover, if they are not hired for process innovation, they can engage in other activities without affecting their process innovation ability. Put together, firm i's technology for process innovation as it hires L_{Z_i} scientists is the following:

$$\dot{Z}_i = \alpha \overline{Z} L_{Z_i},$$

where $\overline{Z}$ denotes the aggregate level technology in the economy and is defined by:

$$\overline{Z} = \frac{\int_{j \in n} Z_j\, dj}{L},$$

and L denotes the total labor force.

A.3 MSOLF vs ESOLF

Let ϱ be the ratio of employees in the large firms to the total number of employees:

$$\varrho = \frac{L_X + L_Z}{L_X + L_Z + L_{X_0}}, \tag{A.1}$$

which is the theory equivalent of ESOLF in the empirical studies. I show that on the BGP, there is a linear relation between s and ϱ, or equivalently MSOLF and ESOLF. The no arbitrage equation for product innovation (*i.e.* setting up new large firms) is: $r + \delta = \frac{D+\dot{V}}{V}$, where $D = PX - W(L_X + L_Z)$ is the dividend. On the BGP, the no arbitrage equation reduces to:

$$\rho + \delta = \frac{\frac{\mathscr{Y}}{n}s - (L_X + L_Z)}{\gamma\frac{\mathscr{Y}}{n}},$$

which can solved for the employees of a large firm:

$$L_X + L_Z = \frac{\mathscr{Y}}{n}s - \gamma\frac{\mathscr{Y}}{n}(\rho + \delta).$$

Also, recall that small firms make no profit, so within an industry, their total sales is equal to their cost of labor:

$$L_{X_0} = \frac{\mathscr{Y}}{n}(1 - s).$$

Thus, I can rewrite the ESOLF:

$$\varrho = \frac{\frac{\mathscr{Y}}{n}s - \gamma\frac{\mathscr{Y}}{n}(\rho + \delta)}{\frac{\mathscr{Y}}{n}s - \gamma\frac{\mathscr{Y}}{n}(\rho + \delta) + \frac{\mathscr{Y}}{n}(1 - s)} = \frac{s - \gamma(\rho + \delta)}{1 - \gamma(\rho + \delta)},$$

which yields the simple linear relation between MSOLF and ESOLF:

$$s = \gamma(\rho + \delta) + \big(1 - \gamma(\rho + \delta)\big)\varrho. \tag{A.2}$$

Note that this equation is derived independent of whether L_z is zero or not. In fact, as long as there is a non-zero product innovation, equation (A.2) holds.

A.4 R&D-intensity vs MSOLF

R&D-intensity (rdI) is defined as the R&D expenditure divided by sales. On the BGP, we have

$$rdI = \frac{L_Z}{\frac{\mathscr{Y}}{n} s} = \frac{\frac{z}{\alpha \frac{n}{L}}}{\mathscr{Y} n s} = \frac{z}{\alpha \frac{\mathscr{Y}}{L} s},$$

which after replacing for $z = -(\rho + \delta) + \alpha \mathscr{Y} s^{\frac{\xi - 1}{\xi}}$ and $\mathscr{Y} = \frac{L}{1 - \rho\gamma}$yields

$$rdI = -\frac{(\rho + \delta)(1 - \rho\gamma)}{\alpha} \frac{1}{s} + \frac{\epsilon - (\epsilon - 1)s - 1}{\epsilon - (\epsilon - 1)s}. \tag{A.3}$$

This is an inverse-U function in the MSOLF. Because MSOLF is linear in ESOLF, then rdI is inverse-U in the ESOLF as well. In fact, substituting s from equation (A.2) into (A.3) gives us R&D-intensity in terms of the ESOLF. It can be easily verified that the graph of R&D-intensity versus ESOLF is an inverse-U similar to that of rdI versus s above, just a little shifted to the left.

A.5 Graphs

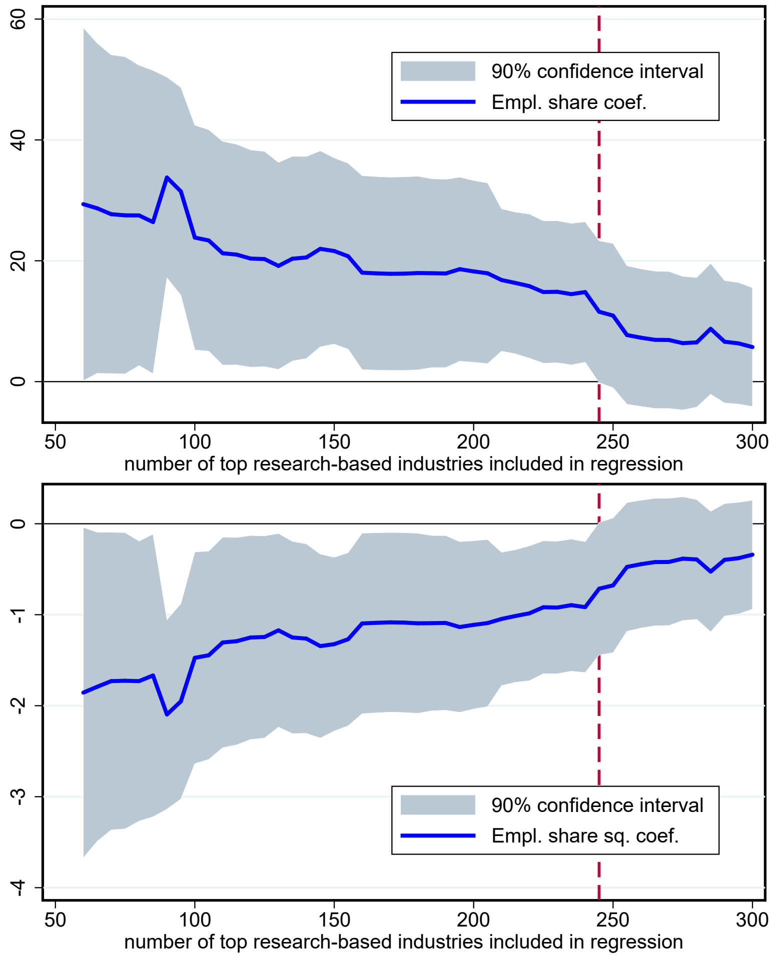

FIGURE A.1: Size and significance of the inverted-U relation between R&D-intensity and ESOLF.

The top panel shows the coefficient of Log(ESOLF+1) and its 90% confidence interval, in the regression of Log(R&D-intensity+1) on Log(ESOLF+1) and Log(ESOLF+1)^2, as I include more research-based industries in the regression. The bottom panel does the same for the coefficient of Log(ESOLF+1)^2. R&D-intensities are constructed using the CCM data for public firms, and ESOLF are constructed for the 6-digit NAICS industries using the SUSB data for years 1998-2014. Regressions include controls for year and industry fixed-effects, and the reported confidence intervals are cluster-robust (for 6-digit NAICS). Notice that the coefficients slowly decline in size, but remain significant until rank $\leqslant 245$ (shown by the red vertical dashed line). The graph shows that the inverted-U relation is fairly robust to the selected sample of research-based industries.

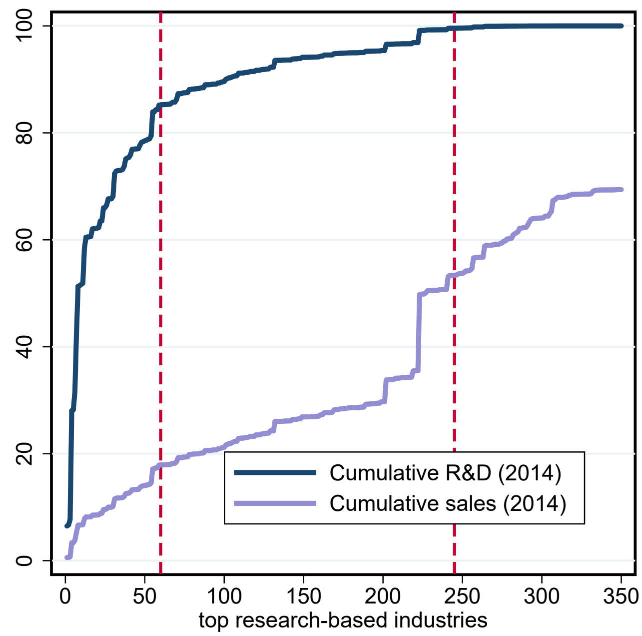

Figure A.2: Cumulative R&D and sales as the number of top research-based industries increase.

On the horizontal axis the 6-digit research-based industries are ranked. On the vertical axis, cumulative R&D and sales add up as the number of top research-based industries increase. The left red dashed-line shows the 60th top research-based industry, at which point more than 85% of total R&D is accounted for, but the figure for sales is only about 18%. The right red dashed-line shows the 240th research-based industry at which point more than 99.5% of total R&D is accounted. As figure A.1 shows, the inverted-U relationship is significant between the two red dashed-lines. Research-based industries are those with high R&D-investment compared to their sales, but the cumulative R&D curve shows that they account for most of the R&D investment as well. Source: R&D and sales data are obtained from the CCM, merged with the SUSB dataset so that it is the same data that is used in 6-digit NAICS regressions. The cumulative graphs are drawn for the last year of the data 2014.

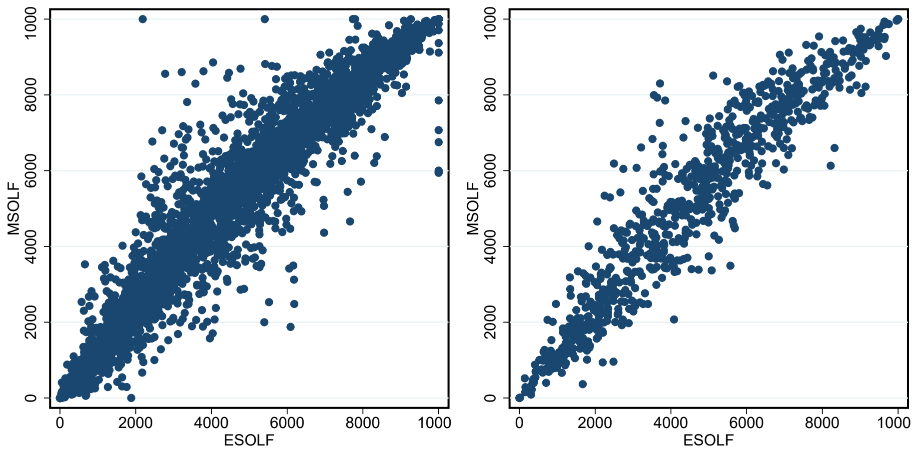

Figure A.3: ESOLF vs MSOLF at the 6-digit and 4-digit NAICS.

Left panel is MSOLF (market share of large firms) vs ESOLF (employee share of large firms) drawn for 6-digit NAICS, and the right panel is the same graph for 4-digit NAICS. Each point is an industry-year constructed from the SUSB dataset, for 2002, 2007, and 2012 (years for which sales exists). The correlation between ESOLF and MSOLF is 95.2% for the left panel, and 94.8% for the right panel, showing that ESOLF is an excellent proxy for MSOLF.

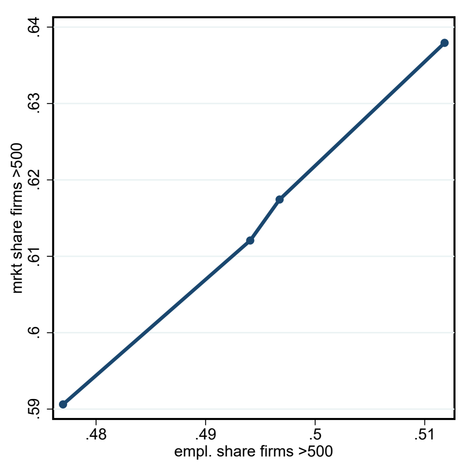

Figure A.4: ESOLF vs MSOLF at the aggregate level.

The graph shows MSOLF (market share of large firms) vs ESOLF (employee share of large firms) at the aggregate level. ESOLF and MSOLF are defined for large firms with than 500 employees, for years 1997, 2002, 2007, and 2012. The correlation between the ESOLF and MSOLF at the aggregate level is 99.9%.

A.6 Tables

Notes on table A.1. The regression equation is: $\log(\text{rdI}_{i,t}+1) = \beta_0+\beta_1 \log(\text{ESOLF}_{i,t}+1) + \beta_2 \log(\text{ESOLF}_{i,t}+1)^2 + \beta X + \alpha_i + u_{i,t}$, where $\text{rdI}_{i,t}$ represent R&D-intensity in basis points, constructed using the CCM data at 6-digit NAICS, and ESOLF is the employee share of large firms (larger than 500 employees) in basis points, constructed using the SUSB data for the years 1998-2014. α_i is the industry fixed effect and other controls are the 'lag of sales growth' and 'year effects', summarized in the βX term. Industries are ranked based on their time-aggregated R&D divided by time-aggregated sales. Each column limits the regression sample to a certain number of top tanked research-based industries, that is stated in the column header. Note that the coefficient are all significant, but slowly decline in size.

Table A.1: R&D intensity vs Employment share of large firms (6-digit NAICS)

	Dependent variable: R&D intensity (log)			
	Rank $\leqslant$ 90	Rank $\leqslant$ 100	Rank $\leqslant$ 150	Rank $\leqslant$ 200
Empl share (log)	33.8***	23.8**	21.6**	18.2**
	(10.1)	(11.3)	(9.37)	(9.15)
Empl share (log) sq	−2.10***	−1.47**	−1.32**	−1.11**
	(0.63)	(0.71)	(0.58)	(0.56)
L.Sales growth	−0.29***	−0.30***	−0.23**	−0.17*
	(0.089)	(0.086)	(0.096)	(0.098)
Industry effect	✓	✓	✓	✓
Year effect	✓	✓	✓	✓
Observations	732	815	1412	1806

Significance levels: * : p <0.1, ** : p <0.05, *** : p <0.01

Standard errors in parentheses are cluster robust for 6d-NAICS.

Notes on table A.2. The regression equation is:

$\log(\text{rdI}_{i,t}+1) = \beta_0+\beta_1 \log(\text{ESOLF}_{i,t}+1) + \beta_2 \log(\text{ESOLF}_{i,t}+1)^2 + \beta X + \alpha_i + u_{i,t}$, where $\text{rdI}_{i,t}$ represent R&D-intensity in basis points, constructed using the CCM data at 4-digit NAICS, and ESOLF is the employee share of large firms (larger than 500 employees) in basis points, constructed using the SUSB data for the years 1998-2014. α_i is the industry fixed effect and other controls include the 'lag of sales growth' and 'year effects', summarized in the βX term. The sample of regressions is the top 60 research-based industries. For robustness check, each specification contains a different set of controls, as shown in the lower part of the table. Notice that the coefficients only change mildly with the omission of controls. The table also shows how the standard errors change when they are not cluster robust.

Table A.2: R&D-intensity vs Employee share of large firms (4-digit NAICS)

	Dependant variable: R&D-intensity (log)				
	(1)	(2)	(3)	(4)	(5)
Empl. sh. (ln)	24.9***	24.6***	24.6***	29.2***	29.4***
	(3.40)	(3.50)	(7.36)	(9.87)	(9.75)
Empl. sh. (ln) sq	−1.50***	−1.49***	−1.49***	−1.78***	−1.80***
	(0.21)	(0.22)	(0.45)	(0.59)	(0.59)
L.Sales growth	0.035***	0.035***	0.035***	0.037***	0.036***
	(0.010)	(0.011)	(0.0080)	(0.0087)	(0.0084)
Industry effect	✗	✗	✗	✓	✓
Year effect	✗	✓	✓	✗	✓
Cluster robust	✗	✗	✓	✓	✓
Observation	836	836	836	836	836

Significance levels: * : p <0.1, ** : p <0.05, *** : p <0.01
Standard errors are reported in parentheses.

Notes on table A.3. The regression equation is:

$$\log(\mathrm{rdI}_{i,t} + 1) = \beta_0 + \beta_1 \log(\mathrm{ESOLF}_{i,t} + 1) + \beta_2 \log(\mathrm{ESOLF}_{i,t} + 1)^2 + \beta X + \alpha_i + u_{i,t},$$

where $\mathrm{rdI}_{i,t}$ represent R&D-intensity in basis points, constructed using the CCM data at 4-digit NAICS, and ESOLF is the employee share of large firms (larger than 500 employees) in basis points, constructed using the SUSB data for the years 1998-2014. α_i is the industry fixed effect and other controls include the 'lag of sales growth' and 'year effects', summarized in the βX term. The sample of regressions is the top 60 research-based industries.

The variable 'RegIndx' represents the regulatory index for each 4-digit NAICS industry. 'RegIndx' is constructed using the RegData by Al-Ubaydli and McLaughlin

(2017), and it is defined as the number of words passed by all regulatory agencies that is 'related' to a specific industry. 'RegIndx' covers 1998-2012. Other variables are: 'Employees' and 'Public firms', that respectively indicate the total number of employees and public firms in a 4-digit NAICS industry, and are constructed using the SUSB and CCM databases.

In order to address the reverse causality of $\log(\mathrm{ESOLF}_{i,t}+1)$, $\log(\mathrm{ESOLF}_{i,t}+1)^2$, I used the following instruments: regulation index variables: $\mathrm{RegIndx}_{i,t+1}$, $\mathrm{RegIndx}^2_{i,t+1}$, and industry variables: $\log(\mathrm{Employees}_{i,t-1})$, $\log(\mathrm{Public\ firms}_{i,t})$, and $\log(\mathrm{Public\ firms}_{i,t})^2$. In the first column (with header OLS), I used all the instruments as regressors, and it is clear that none of them is significant in the presence of ESOLF. Also, it is clear that including the instruments as controls does not make a significant change in other coefficients.

The first stage results are presented in table A.4 below, and show that the instruments pass the usual identification tests.

Notes on table A.5. The regression equation is:
$\log(\mathrm{rdI}_{i,t}+1) = \beta_0 + \beta_1 \log(\mathrm{ESOLF}_{i,t}+1) + \beta_2 \log(\mathrm{ESOLF}_{i,t}+1)^2 + \beta X + \alpha_i + u_{i,t}$, where $\mathrm{rdI}_{i,t}$ represent R&D-intensity in basis points, constructed using the CCM data at 4-digit NAICS, and ESOLF is the employee share of large firms (larger than 500 employees) in basis points, constructed using the SUSB data for the years 1998-2014. α_i is the industry fixed effect and other controls include the 'lag of sales growth' and 'year effects', summarized in the βX term. The variables $\{\log(\mathrm{ESOLF}_{i,t}), \log(\mathrm{ESOLF}_{i,t})^2\}$ are instrumented with regulatory index $\{\mathrm{RegIndx}_{i,t+1}, \mathrm{RegIndx}^2_{i,t+1}\}$ and industry controls
$\{\log(\mathrm{Employees}_{i,t-1}), \log(\mathrm{Public\ firms}_{i,t}), \log(\mathrm{Public\ firms}_{i,t})^2\}$.
Each column uses a different cutoff for the number of top ranked research-based industries that are included in the regression sample (stated in the column header).

Table A.3: R&D-intensity vs Employee share of large firms: reverse causality and IV (4-d NAICS)

	Dependant variable: R&D-intensity (log)		
	OLS	2SLS	LIML
ESOLF (log)	23.3**	237.0***	247.2***
	(9.25)	(86.1)	(91.6)
ESOLF (log) sq.	−1.38**	−14.1***	−14.7***
	(0.55)	(5.14)	(5.47)
(Lag) Sales growth	0.028***	0.055***	0.056***
	(0.0072)	(0.019)	(0.020)
(Fwd) RegIndx	2.22		
	(2.27)		
(Fwd) RegIndx sq.	−0.49		
	(0.43)		
(Lag) Employees (log)	−0.30		
	(0.28)		
Public firms (log)	−1.48		
	(1.54)		
Public firms (log) sq.	0.10		
	(0.073)		
Industry effect	✓	✓	✓
Year effect	✓	✓	✓
Observations	660	660	660

Significance levels: * : $p < 0.1$, ** : $p < 0.05$, *** : $p < 0.01$

Cluster-robust standard errors are reported in parentheses.

Table shows that the inverted-U relation with the reversed-causality addressed, is also robust to the cutoff.

Table A.4: Summary results for the first-stage regressions.

Variable	joint sign. of instr.		under identification		weak identification	
	F(5,57)	p-value	SW $\chi^2(4)$	p-value	SW F(4,57)	p-value
ESOLF (log)	4.44	0.18%	9.49	4.99%	2.28	7.23%
ESOLF (log) sq.	4.47	0.17%	9.55	4.88%	2.29	7.09%

This table presents the first stage regression results for the 2SLS regression in table A.3.

Table A.5: R&D intensity vs Employee share of large firms (IV regressions – 4-digit NAICS)

	Dependent variable: R&D intensity (log)			
	Rank $\leqslant$ 60	Rank $\leqslant$ 65	Rank $\leqslant$ 70	Rank $\leqslant$ 75
ESOLF (log)	237.0***	218.5**	246.9***	231.2**
	(86.1)	(91.1)	(91.4)	(91.2)
ESOLF (log) sq.	−14.1***	−13.2**	−14.8***	−13.9**
	(5.14)	(5.44)	(5.45)	(5.44)
(Lag) Sales growth	0.055***	0.048**	0.053**	0.051**
	(0.019)	(0.020)	(0.021)	(0.020)
Industry effect	✓	✓	✓	✓
Year effect	✓	✓	✓	✓
Observations	660	714	774	823

Significance levels: * : p <0.1, ** : p <0.05, *** : p <0.01

Cluster-robust standard errors are reported in parentheses.

Appendix B

Appendices of Chapter 3

This section contains the appendices on chapter 3.

B.1 Tables and Figures in Section 3

Table B.1: Post-WWII Fiscal Policy

	ALITR	AMDITR	ACGTR	ACITR	ACTR	$\frac{\text{GOV}}{\text{GDP}}$
A. Descriptive statistics:						
Mean	0.206	0.395	0.170	0.320	0.082	0.208
Std. dev.	0.045	0.064	0.034	0.093	0.009	0.021
B. Persistence:						
AR coeff.: ρ_1^x	0.679	1.184	1.132	0.799	0.785	0.910
AR coeff.: ρ_2^x	—	−0.575	−0.308	−0.361	−0.227	−0.378
AR coeff.: ρ_3^x	—	0.139	—	0.021	0.167	—
C. Volatility:						
Std. dev.: σ_ϵ^x	0.008	0.022	0.014	0.028	0.002	0.008
D. Deterministic terms:						
Constant	0.032	0.111	0.020	0.249	0.026	0.087
Polynomial nth-order	2	2	3	1	2	4

Notes: ALITR is the average labor income tax rate for 1946-2014. AMDITR is the average marginal dividend income tax rate for 1946-2003. ACGTR is the average capital gains tax rate for 1954-2013. ACITR is the average corporate income tax rate for 1946-2014. ACTR is the average consumption tax rate for 1946-2014. GOV/GDP (GRATIO) is the government spending to GDP ratio for 1946-2014. The autoregressive (AR) model of order p that we estimate is $x_t = d_t + \sum_{j=1}^{p} \rho_j^x x_{t-j} + \sigma_\epsilon^x \epsilon_t$, with $\epsilon_t \overset{iid}{\sim} \mathcal{N}(0,1)$, where the deterministic term d_t contains a constant, d_0, and nth-order polynomial trends in time, d_t^n. Lag length p is selected via the Akaike Information Criterion (AIC). See Appendix B.2 for further details on data construction, definitions and sources.

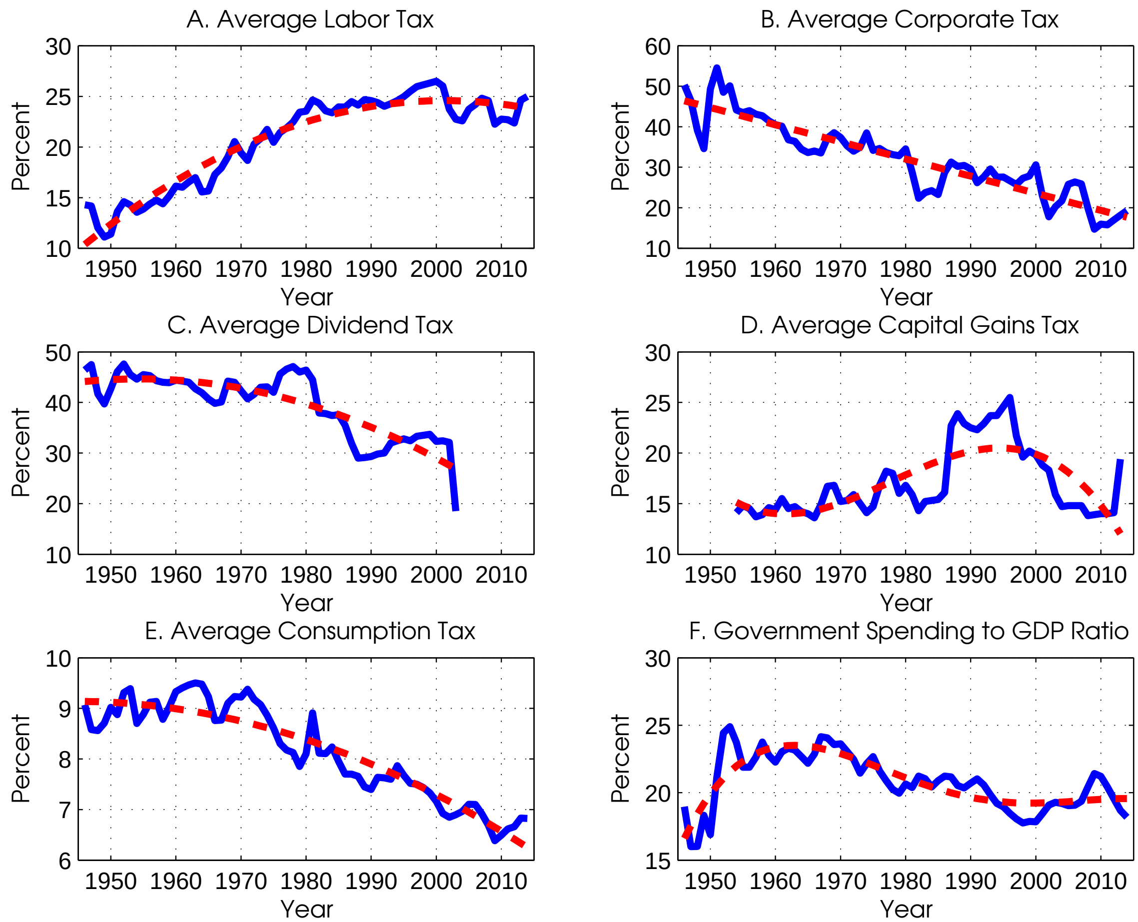

Figure B.1: Post-WWII Fiscal Policy

Notes: In all panels, dashed lines show nth-order polynomial trends. Panel A shows the average labor income tax rate (ALITR) for 1946-2014, together with a second-order polynomial trend. Panel B shows the average corporate income tax rate (ACITR) for 1946-2014, together with a linear trend. Panel C shows the average marginal dividend income tax rate (AMDITR) for 1946-2003, as tabulated by Poterba (2004, p. 172, Table 1), together with a second-order polynomial trend. Panel D shows the average capital gains tax rate (ACGTR) for 1954-2013, together with a third-order polynomial trend. Data on capital gains and taxes paid on capital gains are produced by the U.S. Department of the Treasury, Office of Tax Analysis. Panel E shows the average consumption tax rate (ACTR) for 1946-2014, together with a second-order polynomial trend. Panel F shows the government spending to GDP ratio (GRATIO) for 1946-2014, together with a fourth-order polynomial trend. See Appendix B.2 for further details on data construction, definitions and sources.

Table B.2: Long-Run Responses to Permanent Tax Cuts with 20% Price Markup

	old steady-state	new steady-state (1 pp tax cut)				
		$\tau^d \downarrow$	$\tau^v \downarrow$	$\tau^\pi \downarrow$	$\tau^c \downarrow$	$\tau^l \downarrow$
A. Firms' exit probability of 6.18%:						
Real GDP/TFP growth	2%	0.9%	2.57%	1%	2%	2%
R&D-to-GDP ratio	2.6%	1.34%	3.17%	1.47%	2.6%	2.6%
B. Firms' exit probability of 3.94%:						
Real GDP/TFP growth	2%	1.41%	2.22%	1.47%	2%	2%
R&D-to-GDP ratio	2.6%	2.02%	2.83%	2.08%	2.6%	2.6%

Notes: 1 percentage point (pp) tax cut from steady-state value. See Section 3.5.1 for details on the baseline parametrization of the model.

Table B.3: Long-Run Responses to Permanent Tax Cuts with 10% Price Markup

	old steady-state	new steady-state (1 pp tax cut)				
		$\tau^d \downarrow$	$\tau^v \downarrow$	$\tau^\pi \downarrow$	$\tau^c \downarrow$	$\tau^l \downarrow$
A. Firms' exit probability of 6.18%:						
Real GDP/TFP growth	2%	1.44%	2.30%	1.50%	2%	2%
R&D-to-GDP ratio	2.6%	2.02%	2.93%	2.08%	2.6%	2.6%
B. Firms' exit probability of 3.94%:						
Real GDP/TFP growth	2%	1.65%	2.16%	1.69%	2%	2%
R&D-to-GDP ratio	2.6%	2.28%	2.78%	2.31%	2.6%	2.6%

Notes: 1 percentage point (pp) tax cut from steady-state value. See Section 3.5.1 for details on the baseline parametrization of the model.

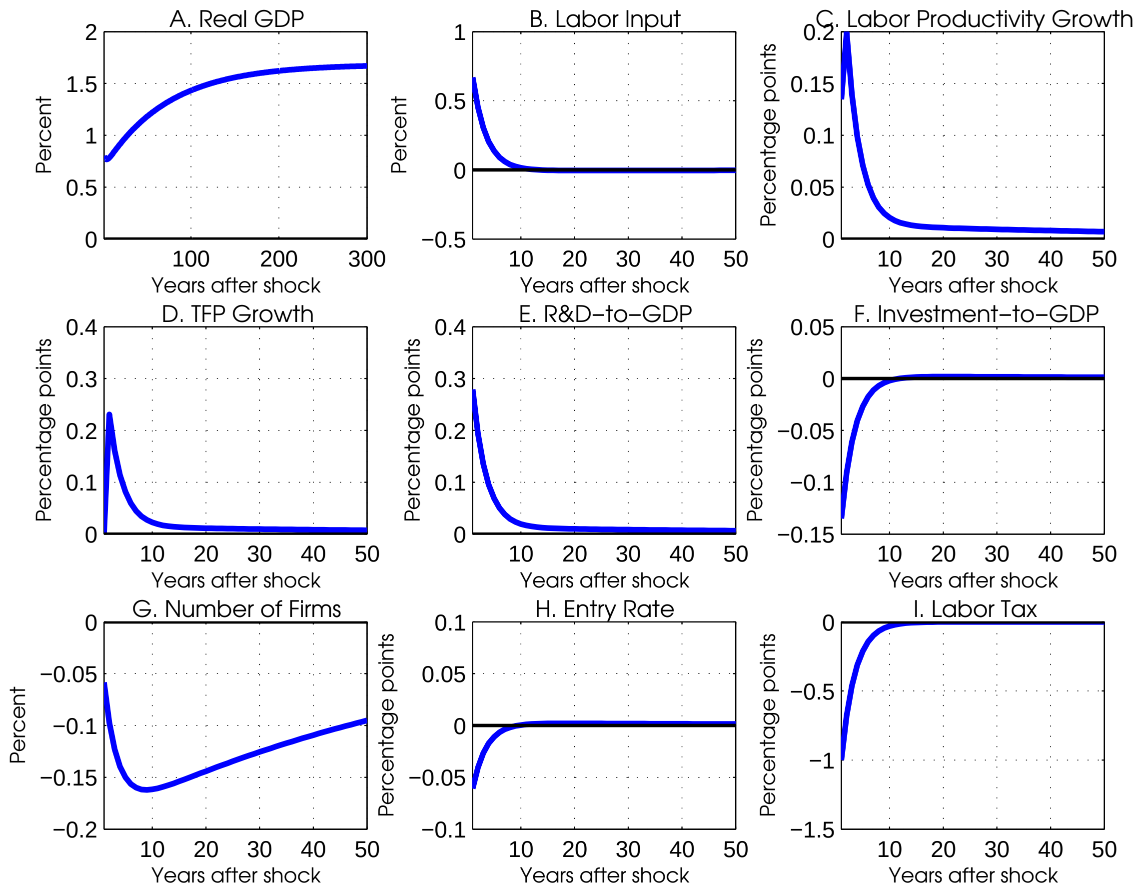

FIGURE B.2: Dynamic Response to a Labor Tax Cut

Notes: See Appendix 3.5.1 for details on the baseline parameterization of the model.

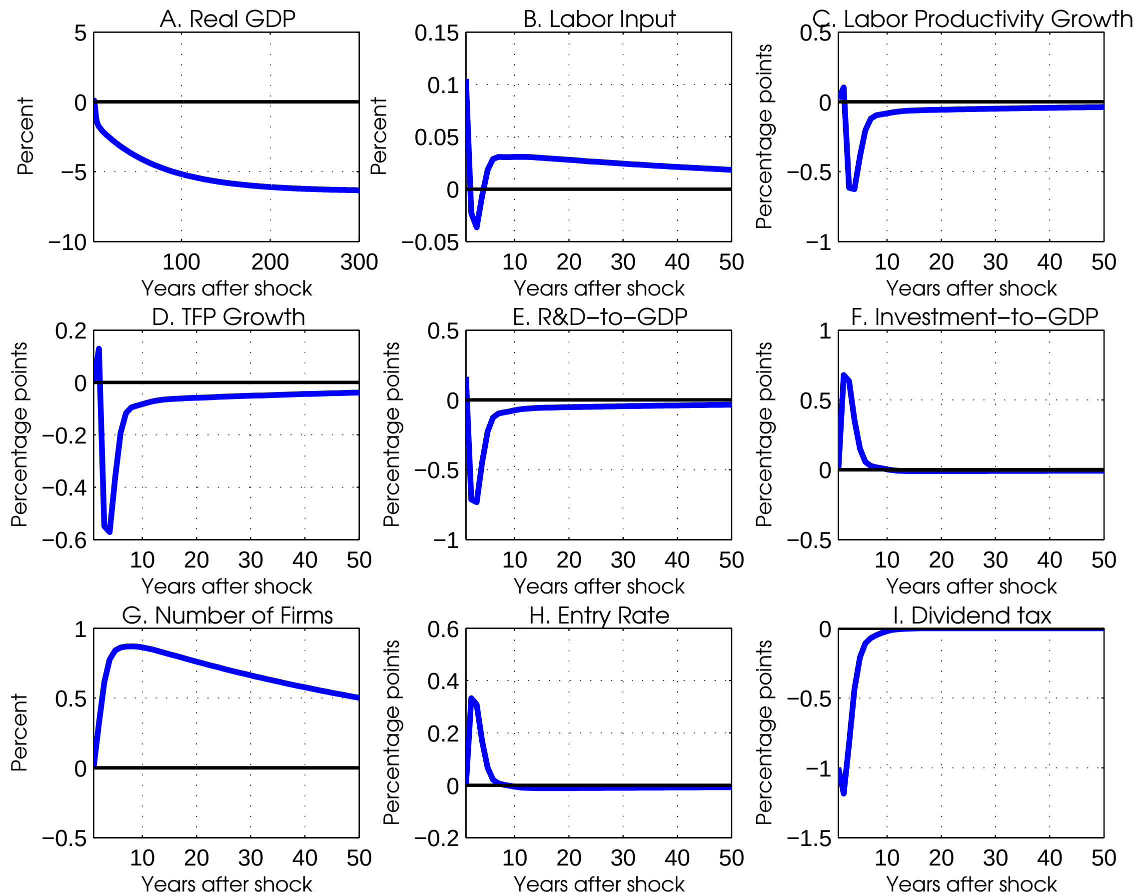

FIGURE B.3: Dynamic Response to a Dividend Tax Cut

Notes: See Appendix 3.5.1 for details on the baseline parameterization of the model.

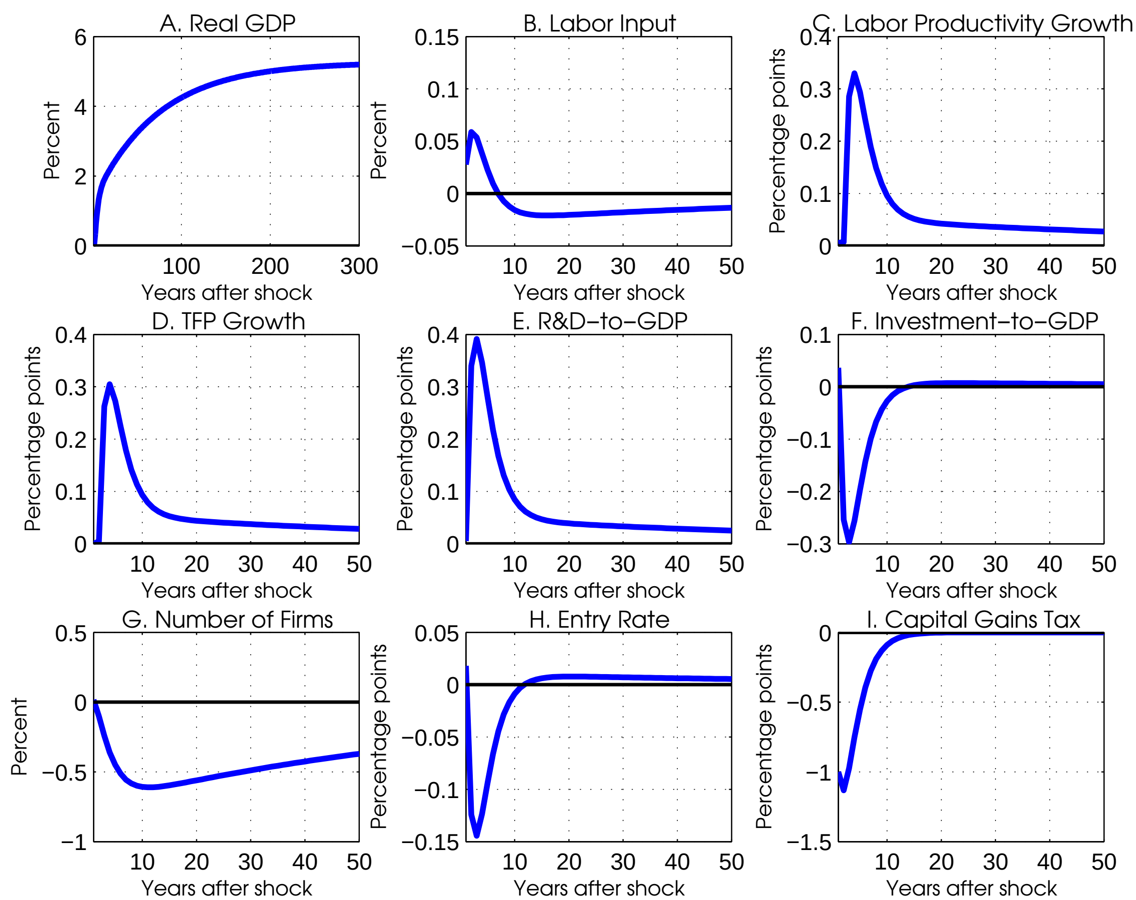

FIGURE B.4: Dynamic Response to a Capital Gains Tax Cut

Notes: See Appendix 3.5.1 for details on the baseline parameterization of the model.

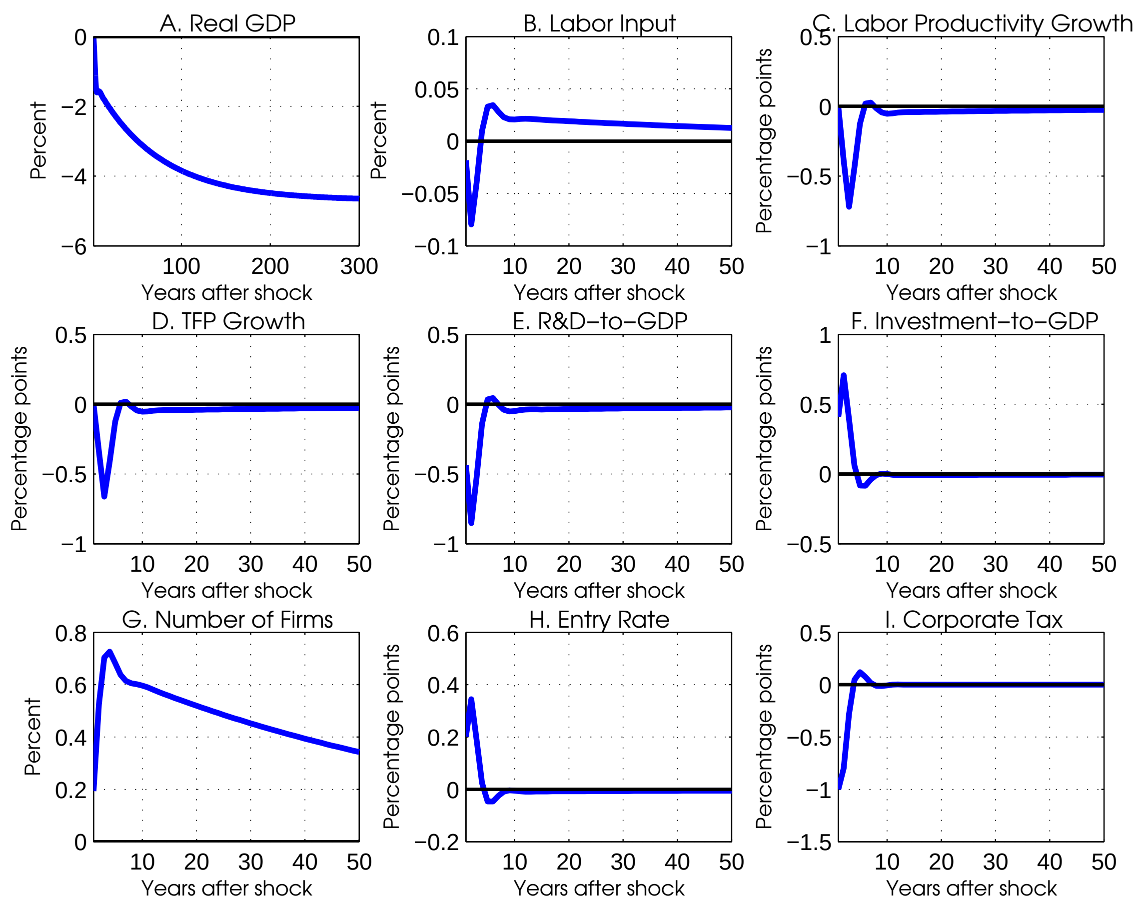

FIGURE B.5: Dynamic Response to a Corporate Tax Cut

Notes: See Appendix 3.5.1 for details on the baseline parameterization of the model.

Table B.4: Variance Decomposition of Aggregate TFP Growth

	full congestion	partial congestion	
	$\eta = 1$	$\eta = 0.95$	$\eta = 0.75$
A. Variances/covariances:			
$\mathrm{Var}(d\ln A_t)$	0.169	0.166	0.153
$\mathrm{Var}(d\ln Z_t)$	0.169	0.173	0.190
$\mathrm{Var}(d\ln N_t)$	0.043	0.045	0.054
$\mathrm{Cov}(d\ln Z_t, d\ln N_t)$	-0.061	-0.065	-0.081
B. Unconditional shares:			
$\mathbf{share}^{\mathrm{TFP}}_{\mathrm{quality}}$	100%	99.9%	98%
$\mathbf{share}^{\mathrm{TFP}}_{\mathrm{entry}}$	0%	0.1%	2%

Notes: Panel A reports the theoretical variances and covariances from the model (in percent). Panel B reports the corresponding variance decompositions, where the shares of the unconditional variance of TFP growth attributed to product quality and firm entry are calculated as $\mathbf{share}^{\mathrm{TFP}}_{\mathrm{quality}} \equiv \frac{\mathrm{Var}(d\ln Z_t)}{\mathrm{Var}(d\ln Z_t)+(1-\eta)^2\mathrm{Var}(d\ln N_t)}$ and $\mathbf{share}^{\mathrm{TFP}}_{\mathrm{entry}} \equiv \frac{(1-\eta)^2\mathrm{Var}(d\ln N_t)}{\mathrm{Var}(d\ln Z_t)+(1-\eta)^2\mathrm{Var}(d\ln N_t)}$, respectively.

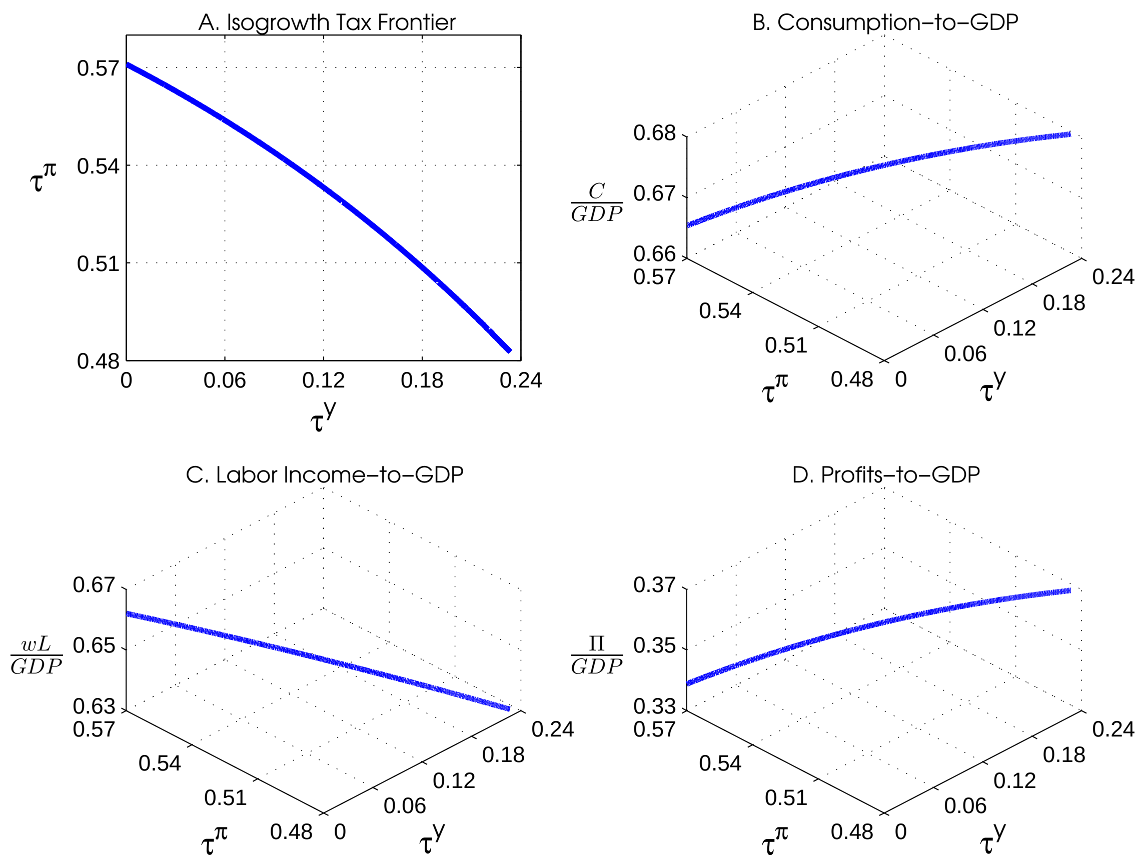

FIGURE B.6: Flat Individual Income Tax

Notes: Panel A shows the combinations of individual income tax rates τ^y on the x-axis and corporate income tax rates τ^π on the y-axis that achieve the 3 percent target for real GDP growth. Panel B through D show the implied share of private consumption in GDP, and the labor and profit income shares of GDP, respectively. The government budget is balanced by lump-sum transfers. See Appendix 3.5.1 for details on the baseline parameterization of the model.

B.2 Data

In this appendix, we provide details on data definitions and sources, and describe how we construct average effective and marginal tax rates. The main source of data is the national income and product account (NIPA) tables by the Bureau of Economic Analysis (BEA). All data items are indexed by table and line numbers. Our approach of calculating average effective tax rates closely follows that of Mendoza et al. (1994). We aggregate all levels of the government (federal, state and local) into one general government sector.

The **average corporate income tax rate** (**ACITR**) is defined as ACITR $\equiv$ CT/CP, where CT is federal, state and local taxes on corporate income (NIPA Table 3.1 line 5), excluding Federal Reserve banks (NIPA Table 3.2 line 8), and CP is the **corporate income tax base**, that consists of corporate profits (NIPA Table 1.12 line 13), excluding Federal Reserve banks profits (NIPA Tables 6.16 A-B-C-D line 11). Mertens and Ravn (2013) follow a similar methodology but they restrict their calculations to the federal government.

The **average consumption tax rate** (**ACTR**) is defined as

$$\text{ACTR} \equiv \frac{\text{TPI} - \text{PRT}}{\text{PCE} - (\text{TPI} - \text{PRT})},$$

where TPI is **taxes on production and imports** (NIPA Table 3.1 line 4), PRT is **property taxes** (NIPA Table 3.3 line 8), and PCE is **personal consumption expenditures** on durables, nondurables, and services (NIPA Table 1.1.5 line 2).[1]

The **average personal income tax rate** (**APITR**) is defined as

[1] Taxes on production and imports consists of federal excise taxes and custom duties and of state and local sales taxes, property taxes (including residential real estate taxes), motor vehicle licenses, severance taxes, special assessments, and other taxes.

$$\text{APITR} \equiv \frac{\text{PIT}}{\text{WSA} + \text{PRI}/2 + \text{CI}},$$

where PIT is **personal income taxes**, that consists of federal personal income taxes (NIPA Table 3.2 line 3) and state and local personal income taxes (NIPA Table 3.3 line 4), WSA is **wage and salaries** (NIPA Table 1.12 line 3), PRI is **proprietors' income** (NIPA Table 1.12 line 9), CI $\equiv$ PRI/2 + RI + DI + NI is **capital income**, RI is **rental income** (NIPA Table 1.12 line 12), DI is **net dividends** (NIPA Table 1.12 line 16), and NI is **net interest** (NIPA Table 1.12 line 18). As discussed in Joines (1981), the imputation of proprietor's income to capital and labor income is somewhat arbitrary. We here follow Jones (2002) and split proprietor's income evenly between capital and labor income.

The **average labor income tax rate** (**ALITR**) is then defined as

$$\text{ALITR} \equiv \frac{\text{APITR} \times (\text{WSA} + \text{PRI}/2) + \text{CSI}}{\text{CEM} + \text{PRI}/2},$$

where CSI is **contributions for government social insurance** (NIPA Table 3.1 line 7), and CEM is **compensation of employees** (NIPA Table 1.12 line 2). The calculations of APITR and ALITR are based on Jones (2002). Leeper et al. (2010) follow a similar methodology but they restrict their calculations to the federal government.

The **average marginal dividend income tax rate** (**AMDITR**) is from Poterba (2004, p. 172, Table 1). AMDITRs after 1960 are based on tabulations from the NBER TAXSIM model, and on data from the U.S. Department of the Treasury, Statistics of Income, for earlier years. AMDITR includes the federal marginal income tax rate plus an estimate of the state marginal income tax rate, net of federal income tax deductibility. The **average capital gains tax rate** (**ACGTR**) is based on data from the U.S. Department of the Treasury, Office of Tax Analysis, and available at `https://www.treasury.gov/resource-center/tax-policy/Pages/Tax-Analysis-and-Research.aspx`.

The **government spending to GDP ratio** (**GRATIO**) is defined as GRATIO ≡ GOV/GDP, where GOV is **government consumption expenditures and gross investment**, that includes federal (national defense plus nondefense), state and local government level (NIPA Table 1.1.5 line 22) and GDP is **gross domestic product** (NIPA Table 1.1.5 line 1). The **tax revenues to GDP ratio** (**TRATIO**) is calculated as TRATIO ≡ TR/GDP, where TR ≡ PCT+TPI+CT+CSI, and PCT is federal, state and local **personal current taxes** (NIPA Table 3.1 line 3). Blanchard and Perotti (2002) and Mertens and Ravn (2014), among others, follow a similar methodology but they restrict their calculations to the federal government. Consumption expenditures (durables, nondurables, and services) to GDP ratio (CRATIO) is calculated as PCE/GDP, where PCE is **personal consumption expenditures** (NIPA Table 1.1.5 line 2).

B.3 Model Derivations

In this appendix, we first provide details on the derivation of the equations presented in the main text of the paper and then discuss how we solve the model.

B.3.1 Cum-Dividend Value of the Firm

In symmetric equilibrium, after-tax gross return to the market portfolio is $\tilde{R}_t^a = (1-\delta) R_{i,t}^a$, where $R_{i,t}^a = \left[\left(1-\tau_t^d\right) D_{i,t} + \left(1-\tau_t^v\right) V_{i,t} + \tau_t^v V_{i,t-1}\right] / V_{i,t-1}$ and $V_{i,t}$ denotes the value of the firm after dividends payout (ex-dividend value). The asset pricing equation for corporate equity shares reads:

$$1 = \mathbb{E}_t \left[(1-\delta)\, M_{t,t+1} R^a_{i,t+1} \right], \quad \text{with} \quad M_{t,t+1} \equiv \beta \, \frac{u_c(c_{t+1}, l_{t+1})}{u_c(c_t, l_t)} \left(\frac{1+\tau^c_t}{1+\tau^c_{t+1}} \right). \tag{B.1}$$

Using the expression for $R^a_{i,t}$, the asset pricing equations for corporate equity shares in period t and $t+1$ are, respectively:

$$V_{i,t} = \frac{\mathbb{E}_t \left\{ (1-\delta) M_{t,t+1} \left[\left(1-\tau^d_{t+1}\right) D_{i,t+1} + \left(1-\tau^v_{t+1}\right) V_{i,t+1} \right] \right\}}{1 - \mathbb{E}_t \left[(1-\delta) M_{t,t+1} \tau^v_{t+1} \right]}; \tag{B.2}$$

$$V_{i,t+1} = \frac{\mathbb{E}_{t+1} \left\{ (1-\delta) M_{t+1,t+2} \left[(1-\tau^d_{t+2}) D_{i,t+2} + (1-\tau^v_{t+2}) V_{i,t+2} \right] \right\}}{1 - \mathbb{E}_{t+1} \left[(1-\delta) M_{t+1,t+2} \tau^v_{t+2} \right]}. \tag{B.3}$$

Iterating equation (B.2) one period forward and using (B.3) yields:

$$V_{i,t} = \frac{\mathbb{E}_t \left[(1-\delta) M_{t,t+1} (1-\tau^d_{t+1}) D_{i,t+1} \right]}{1 - \mathbb{E}_t \left[(1-\delta) M_{t,t+1} \tau^v_{t+1} \right]} + \tag{B.4}$$

$$+ \frac{\mathbb{E}_t \left\{ (1-\delta) M_{t,t+1} (1-\tau^v_{t+1}) \mathbb{E}_{t+1} \left[(1-\delta) M_{t+1,t+2} (1-\tau^d_{t+2}) D_{i,t+2} \right] \right\}}{\left(1 - \mathbb{E}_t \left[(1-\delta) M_{t,t+1} \tau^v_{t+1} \right]\right) \times \left(1 - \mathbb{E}_{t+1} \left[(1-\delta) M_{t+1,t+2} \tau^v_{t+2} \right]\right)} + \tag{B.5}$$

$$+ \frac{\mathbb{E}_t \left\{ (1-\delta) M_{t,t+1} (1-\tau^v_{t+1}) \mathbb{E}_{t+1} \left[(1-\delta) M_{t+1,t+2} (1-\tau^v_{t+2}) V_{i,t+2} \right] \right\}}{\left(1 - \mathbb{E}_t \left[(1-\delta) M_{t,t+1} \tau^v_{t+1} \right]\right) \times \left(1 - \mathbb{E}_{t+1} \left[(1-\delta) M_{t+1,t+2} \tau^v_{t+2} \right]\right)}. \tag{B.6}$$

Continuing with forward iteration, and using the standard transversality condition on the terminal value of the firm, yields:

$$V_{i,t} = \left(\frac{1}{1-\tau^v_t} \right) \mathbb{E}_t \sum_{j=1}^{\infty} \left(\prod_{k=1}^{j} \tilde{M}_{t+k-1,t+k} \right) \left(1-\tau^d_{t+j}\right) D_{i,t+j}, \tag{B.7}$$

where the factor $\tilde{M}_{t,t+k}$ is defined as

$$\tilde{M}_{t+k-1,t+k} \equiv \frac{(1-\delta)M_{t+k-1,t+k}(1-\tau^v_{t+k-1})}{1-\mathbb{E}_{t+k-1}\left[(1-\delta)M_{t+k-1,t+k}\tau^v_{t+k}\right]}, \tag{B.8}$$

and $M_{t+k-1,t+k}$ is the consumption-tax-adjusted SDF, as defined in (B.1). Next, using the ex-dividend value of the firm in equation (B.7), the incumbent intermediate producer maximizes the following cum-dividend firm value:

$$(1-\tau^d_t)D_{i,t} + \mathbb{E}_t \sum_{j=1}^{\infty} \left(\prod_{k=1}^{j} \tilde{M}_{t+k-1,t+k} \right) \left(1-\tau^d_{t+j}\right) D_{i,t+j} + \tau^v_t V_{i,t-1}. \tag{B.9}$$

Note that in the expression (B.9), the last term $\tau^v_t V_{i,t-1}$ on the right-hand side is irrelevant for the firm's value maximization problem, as it is independent of current firm's choices.

B.3.2 Equilibrium Conditions and Solution Method

Here we list the equilibrium conditions that we use to compute the equilibrium of the model. Specifically, we consider a first-order log-linear approximation of the equilibrium around the non-stochastic steady state of the model. The system of equilibrium conditions is:

$$C_t + G_t + \tilde{N}_{t-1} I_t + \nu X_t \left(\frac{\tilde{N}_t}{1-\delta} - \tilde{N}_{t-1} \right) + \tilde{N}_{t-1} X_t + \phi \tilde{N}_{t-1} Z_{t-1} = Y_t; \tag{B.10}$$

$$Y_t = \theta^{\frac{2\theta}{1-\theta}} L_t Z_{t-1} \tilde{N}_{t-1}^{1-\eta}; \tag{B.11}$$

$$\gamma L_t^{\vartheta} C_t = \frac{(1-\tau_t^l)}{(1+\tau_t^c)} w_t; \tag{B.12}$$

$$1 = \mathbb{E}_t \left[M_{t,t+1} R_t^b \right], \quad \text{with} \quad M_{t,t+1} \equiv \beta \, \frac{C_t}{C_{t+1}} \left(\frac{1+\tau_t^c}{1+\tau_{t+1}^c} \right); \tag{B.13}$$

$$1 = \mathbb{E}_t \left[M_{t,t+1} \tilde{R}_{t+1}^a \right]; \tag{B.14}$$

$$\tilde{R}_{t+1}^a \equiv (1-\delta) \left[\left(1 - \tau_{t+1}^d \right) \frac{D_{t+1}}{V_t} + \left(1 - \tau_{t+1}^v \right) \left(\frac{V_{t+1} - V_t}{V_t} \right) + 1 \right]; \tag{B.15}$$

$$w_t = (1-\theta)\, \theta^{\frac{2\theta}{1-\theta}} Z_{t-1} \tilde{N}_{t-1}^{1-\eta}; \tag{B.16}$$

$$\tilde{N}_{t-1}^{\eta} X_t = \theta^{\frac{2}{1-\theta}} Z_{t-1} L_t; \tag{B.17}$$

$$Z_t = Z_{t-1} + I_t; \tag{B.18}$$

$$V_t = \nu X_t; \tag{B.19}$$

$$1 = \mathbb{E}_t \left\{ (1-\delta)\, M_{t,t+1} \left[\frac{(1-\tau_t^v)(1-\tau_{t+1}^d)(1-\tau_{t+1}^\pi)}{(1-\tau_t^d)(1-\tau_t^\pi)} \left[\left(\frac{1-\theta}{\theta} \right) \frac{\alpha X_{t+1}}{Z_t} + 1 \right] + \tau_{t+1}^v \right] \right\}; \tag{B.20}$$

$$F_t = \left(\frac{1-\theta}{\theta} \right) \theta^{\frac{2}{1-\theta}} \left(\frac{L_t}{\tilde{N}_{t-1}^{\eta}} \right) Z_{t-1} - \phi Z_{t-1}; \tag{B.21}$$

$$D_t = (1-\tau_t^\pi)(F_t - I_t); \tag{B.22}$$

$$G_t + \Omega_t = T_t; \tag{B.23}$$

$$G_t = g_t \big[Y_t - \tilde{N}_{t-1}(X_t + \phi Z_{t-1}) \big]; \tag{B.24}$$

$$T_t = \tau_t^c C_t + \tau_t^l w_t L_t + \tilde{N}_{t-1} \left[\tau_t^d D_t + \tau_t^v (V_t - V_{t-1}) + \tau_t^\pi \, (F_t - I_t) \right]. \tag{B.25}$$

To compute the approximate equilibrium of the model around the steady state, in the system (B.10)-(B.25), we divide the variables with positive steady-state growth by Z_{t-1}. For example, $\hat{c}_t \equiv C_t/Z_{t-1}$. Variables with hats indicate series detrended by the quality index.

B.3.3 Rate of Return to Equity and R&D Investment Schedules

Here we provide details on the derivation of the rate of return to incumbents' investment (RRI) and the rate of return to entrants' investment (RRE), or analogously to firm creation investment. We interpret RRI and RRE as investment schedules as represented in (i_t, r^a_{t+1}) space, where $i_t \equiv I_t/Z_{t-1}$ is the current R&D investment rate and r^a_{t+1} is the rate of return to corporate equity one period ahead.

Rate of return to incumbents' investment (RRI). Dropping expectations and using the household's first-order intertemporal condition for equity in (B.14), it yields:

$$\frac{1}{\tilde{R}^a_{t+1}} = M_{t,t+1}. \tag{B.26}$$

Replacing the relationship in (B.26) into the first-order intertemporal condition for R&D investment in (B.20), and dropping expectations, it yields:

$$R^a_{t+1} = \frac{(1-\tau^v_t)(1-\tau^d_{t+1})^2}{(1-\tau^d_t)^2} \left[\left(\frac{1-\theta}{\theta} \right) \alpha x_{t+1} + 1 \right] + \tau^v_{t+1}, \tag{B.27}$$

where $R^a_{t+1} \equiv 1 + r^a_{t+1}$ is the gross rate of return to corporate equity and $x_{t+1} \equiv X_{t+1}/Z_t$ is the quality-adjusted firm size. In equation (B.27), we use the restriction $\tau^d_t = \tau^\pi_t$ for all $t \geqslant 0$ to simplify notation, but it is inessential for the derivations here. We refer to the expression in equation (B.27) as the incumbents' investment schedule (RRI schedule). We stress that the RRI schedule is a flat line in the (i_t, r^a_{t+1}) space. This reflects the "bang-bang" property of the investment problem at the individual firm-level.

Rate of return to entrants' investment (RRE). The expression in (B.15) yields the after-tax rate of return to corporate equity in symmetric equilibrium:

$$r^a_{t+1} = \left(1-\tau^d_{t+1}\right)\frac{D_{t+1}}{V_t} + \left(1-\tau^v_{t+1}\right)\left(\frac{V_{t+1}-V_t}{V_t}\right). \tag{B.28}$$

Next, using the expression for dividends $D_t = (1-\tau^\pi_t)(F_t - I_t)$ in (B.22), it yields:

$$r^a_{t+1} = \left(1-\tau^d_{t+1}\right)^2\left(\frac{F_{t+1}-I_{t+1}}{V_t}\right) + \left(1-\tau^v_{t+1}\right)\left(\frac{V_{t+1}-V_t}{V_t}\right). \tag{B.29}$$

In equation (B.29), we use again the restriction $\tau^d_t = \tau^\pi_t$ for all $t \geqslant 0$ to simplify notation, but it is inessential for the derivations here. Using the free-entry condition $V_t = \nu X_t$ in (B.19), and multiplying and dividing by Z_t the first two terms on the right-hand side of (B.29), it yields:

$$r^a_{t+1} = \left(1-\tau^d_{t+1}\right)^2\left[\frac{F_{t+1}/Z_t - I_{t+1}/Z_t}{\nu X_t/Z_t}\right] + \left(1-\tau^v_{t+1}\right)\left[\frac{X_{t+1}/Z_t - X_t/Z_t}{X_t/Z_t}\right]. \tag{B.30}$$

Using the expression for the gross cash flow $F_t = (p_t - 1)X_t - \phi Z_{t-1}$, jointly with the constant markup pricing rule $p_t = 1/\theta$, it yields the schedule linking the rate of return to equity one period ahead, r^a_{t+1}, to the current R&D investment rate, i_t:

$$r^a_{t+1} = \left(1-\tau^d_{t+1}\right)^2\left[\frac{\left(\frac{1-\theta}{\theta}\right)x_{t+1} - \phi - i_{t+1}}{\nu x_t}\right](1+i_t) + \left(1-\tau^v_{t+1}\right)\left[\frac{x_{t+1}(1+i_t)}{x_t} - 1\right]. \tag{B.31}$$

We refer to the expression in equation (B.31) as the entrants' investment schedule (RRE schedule). We stress that the RRE schedule is upward sloping in the (i_t, r^a_{t+1}) space.

The intersection of the RRI and RRE schedules describes the investment rate and the rate of return to equity as implied by the no-arbitrage condition between incumbents' investment and firm creation investment.

B.3.4 Production Innovation and Quality Innovation Locus

Here we provide details on the derivation of the product (PI) and quality innovation (QI) locus. The PI and QI locus jointly determine the gross growth rate, $z_t \equiv Z_t/Z_{t-1}$, and the quality-adjusted firm size, $x_t \equiv X_t/Z_{t-1}$, in the steady state of the model with constant tax rates. In steady state, equation (B.27) reduces to:

$$R^a = (1-\tau^v)\left[\left(\frac{1-\theta}{\theta}\right)\alpha x + 1\right] + \tau^v. \tag{B.32}$$

Next, using the relationship in (B.26), and the expression for the effective SDF in (B.13), and realizing that in the steady state aggregate consumption grows at the same rate of quality improvement, it yields the QI locus in the (x, z) space:

$$z = \beta(1-\delta)\left\{(1-\tau^v)\left[\left(\frac{1-\theta}{\theta}\right)\alpha x + 1\right] + \tau^v\right\}. \tag{B.33}$$

Next, in the steady state, equation (B.31) reduces to:

$$R^a = \left(1-\tau^d\right)^2\left[\left(\frac{1-\theta}{\nu\theta}\right) - \frac{\phi+i}{\nu x}\right](1+i) + (1-\tau^v)\, i + 1. \tag{B.34}$$

Again, using the relationship in (B.26), and the steady-state expression for the effective SDF in (B.13), and $z = 1+i$, it yields the PI locus in the (x, z) space:

$$z = \beta(1-\delta)\left\{\left(1-\tau^d\right)^2\left[\left(\frac{1-\theta}{\nu\theta}\right) - \frac{\phi+z-1}{\nu x}\right]z + (1-\tau^v)\, z + \tau^v\right\}. \tag{B.35}$$

B.3.5 National Income and Product Accounts

Here we provide details on the calculation of gross domestic product (GDP) in the model in relation to the U.S. national income and product accounts (NIPA). In NIPA's accounting methodology, GDP can be measured as: (i) the sum of the value added generated at each stage of production ("value-added approach"); (ii) the sum of goods and services sold to final users ("expenditures approach"); and (iii) the sum of income payments and other costs incurred in the production of goods and services ("income approach"). Next, we calculate GDP in the model according to these three different approaches.

Value-added approach. According to the value-added approach, GDP equals the sum of the valued added generated at each stage of production. In the product side of the model accounts, there are two stages of production: (i) production of the final good in the final good sector, and (ii) production of the intermediate good in the corporate sector. Value-added (VA) in the final good sector is $\mathrm{VA}_t^{\mathrm{FS}} = Y_t - p_t \tilde{N}_{t-1} X_t$, where Y_t is sales of final goods and $p_t \tilde{N}_{t-1} X_t$ is the value of intermediate inputs used up in production. (Note that we take the final good as the numeraire, whose price is then normalized to one.) Value-added in the corporate sector is $\mathrm{VA}_t^{\mathrm{CS}} = p_t \tilde{N}_{t-1} X_t - \tilde{N}_{t-1} X_t - \phi Z_{t-1}$, where $p_t \tilde{N}_{t-1} X_t$ is sales of intermediate goods and $\tilde{N}_{t-1} X_t + \phi Z_{t-1}$ is production costs. The production technology in the corporate sector requires one unit of final good per unit of intermediate good produced, such that $\tilde{N}_{t-1} X_t$ is intermediate expenses on goods used up as inputs into the production of intermediate goods. Note that we treat R&D expenditures in the corporate sector as fixed assets, which is consistent with the current NIPA approach. As a result, in the model, $\mathrm{GDP}_t = \mathrm{VA}_t^{\mathrm{FS}} + \mathrm{VA}_t^{\mathrm{CS}} = Y_t - \tilde{N}_{t-1} X_t - \phi Z_{t-1}$.

Expenditures approach. According to the expenditures approach, GDP equals the sum of (i) *personal consumption expenditures*, (ii) *gross private fixed investment*,

(iii) *change in private inventories*, (iv) *net exports of goods and services*, (v) *government consumption expenditures and gross investment*. (Note that, in the model, change in private inventories and net exports of goods and services are identically zero.) Consistently with the current NIPA approach, we treat R&D expenditures as fixed assets, such that R&D is recorded as gross private fixed investment. Also, according to the System of National Accounts, 2008, (2008 SNA), R&D is defined as "creative work undertaken on a systematic basis to increase the stock of knowledge, and use of this stock of knowledge for the purpose of discovering or developing new products, including improved versions or qualities of existing products, or discovering or developing new or more efficient processes of production." (See `http://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf` for further details on the treatment of R&D in national accounts.) We classify investment in quality improvements, $\tilde{N}_{t-1}I_t$, as R&D expenditures, and sunk entry costs, $\nu X_t \Delta_{N,t}$, as private fixed investment. As a result, in the model, $\text{GDP}_t = C_t + G_t + \tilde{N}_{t-1}I_t + \nu X_t \Delta_{N,t}$, where C_t and G_t are personal and government consumption expenditures, respectively, and $\tilde{N}_{t-1}I_t + \nu X_t \Delta_{N,t}$ is gross private fixed investment.

Income approach. According to the income approach, GDP equals the sum of income payments and other costs incurred in the production of goods and services. In the model, labor income represents a constant share of gross output: $w_t L_t = (1-\theta)\, Y_t$. The recognition of R&D expenditures as gross private fixed investment also affects the income side of the accounts (both in the model and NIPA data), as gross domestic income (GDI) equals gross domestic product (GDP). According to the current NIPA approach, R&D expenditures are entirely attributed to corporate profits. Thus, in the income side of the model accounts, we calculate corporate profits as $\tilde{N}_{t-1}\Pi_t + \tilde{N}_{t-1}I_t$, where Π_t is operating profit. Note that, in the model, $p_t \tilde{N}_{t-1} X_t = \theta Y_t$. As a result, in the model, $\text{GDI}_t \equiv \text{GDP}_t = Y_t - \tilde{N}_{t-1}X_t - \phi Z_{t-1}$.

B.4 Model Results

In this appendix, we provide additional results based on impulse response functions (IRFs) to tax shocks under alternative parameterizations of the model, and steady-state responses to tax cuts in the variant of the model with a fixed number of firms.

B.4.1 IRFs to Tax Shocks with Higher Firm's Exit Probability

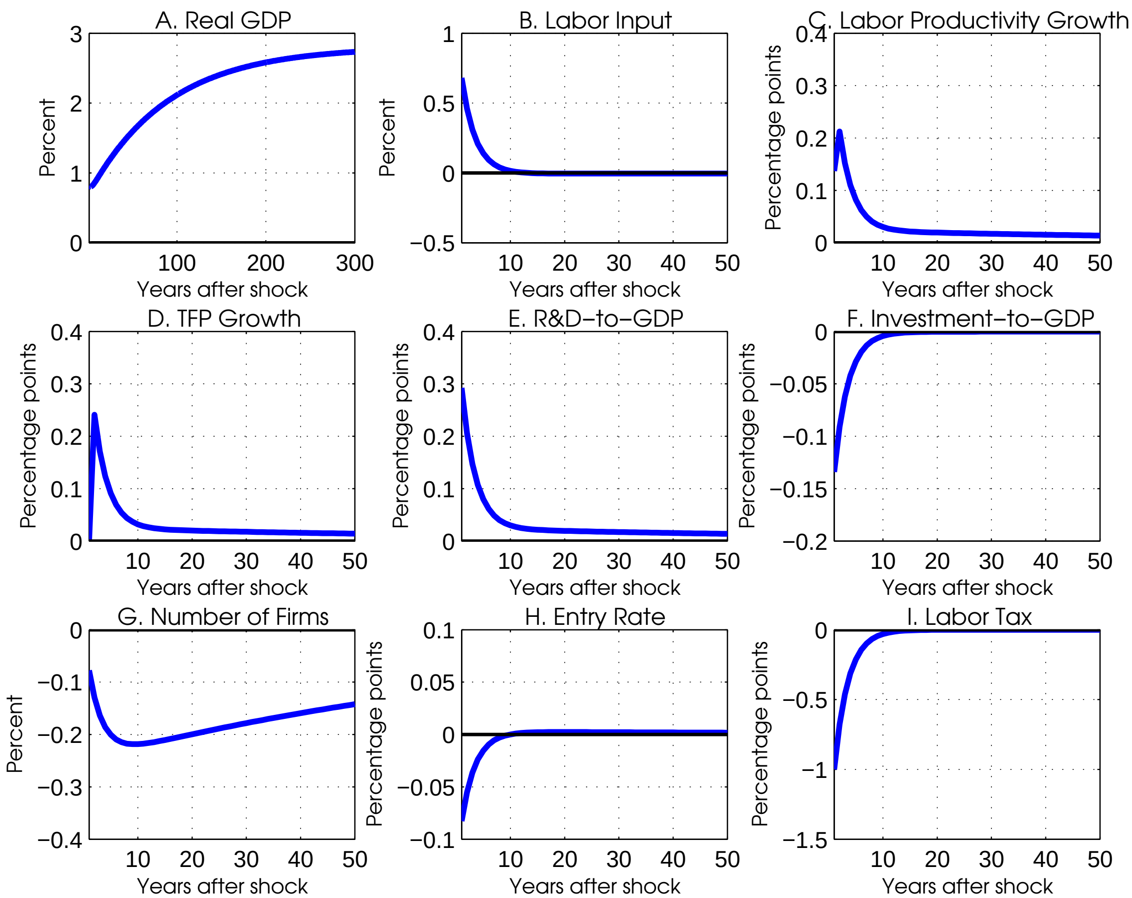

FIGURE C.1: Dynamic Response to a Labor Tax Cut

Notes: Firm's exit probability of 6.18 percent. See Appendix 3.5.1 for details on the baseline parameterization of the model.

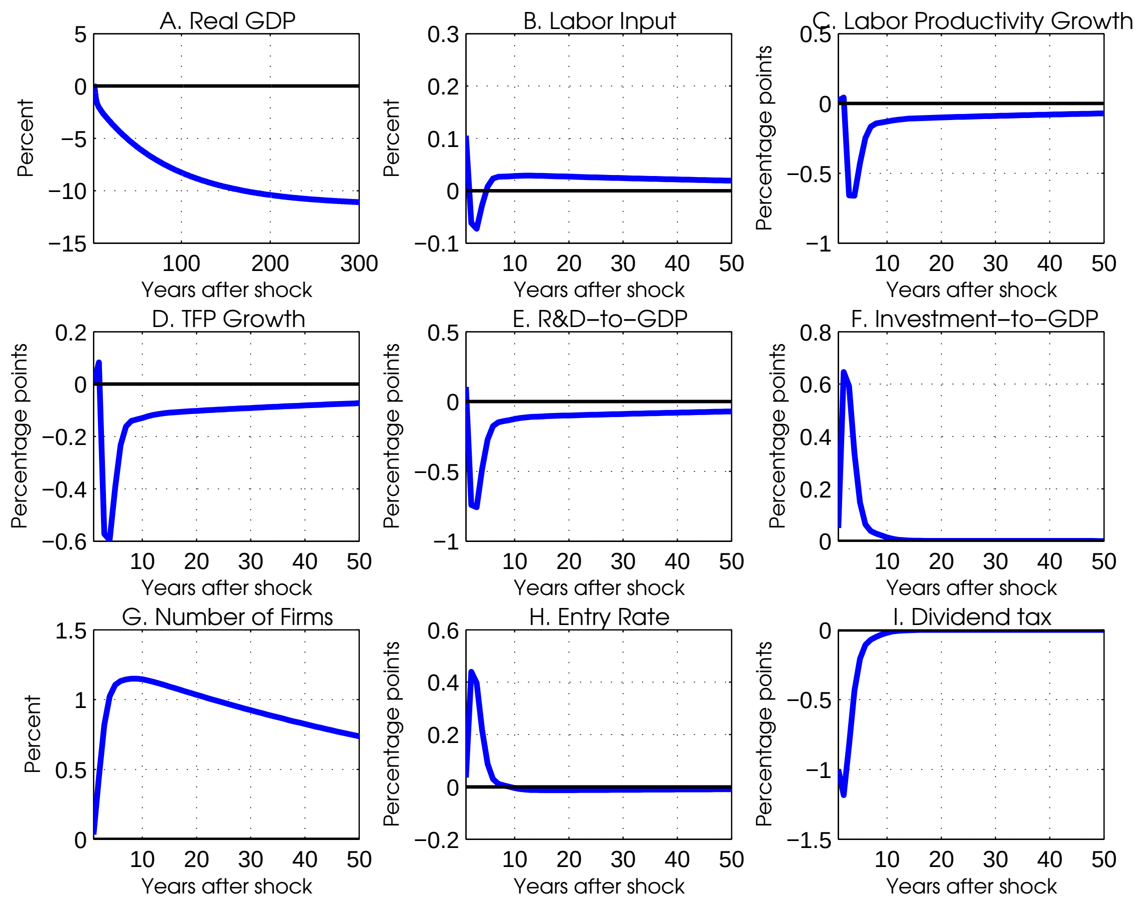

FIGURE C.2: Dynamic Response to a Dividend Tax Cut

Notes: Firm's exit probability of 6.18 percent. See Appendix 3.5.1 for details on the baseline parameterization of the model.

B.4.2 IRFs to Tax Shocks with Fixed Number of Firms

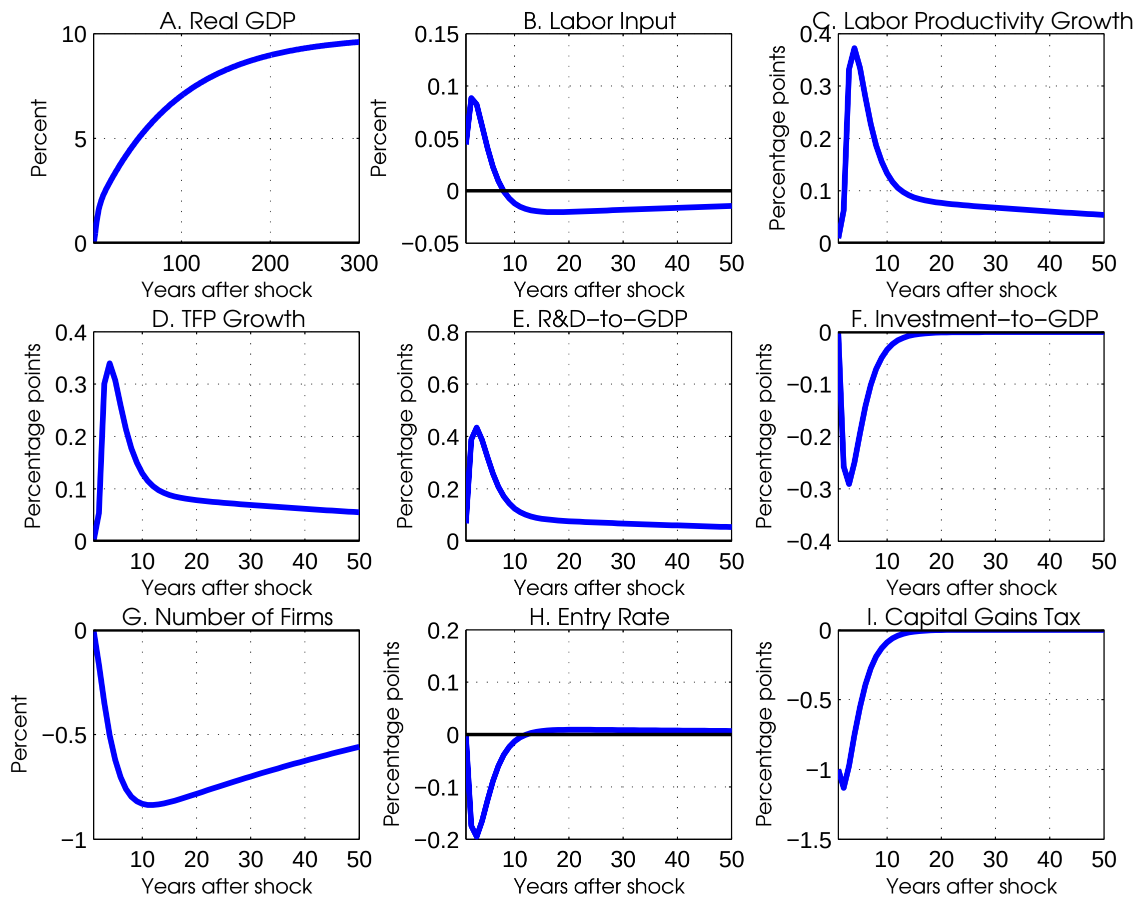

FIGURE C.3: Dynamic Response to a Capital Gains Tax Cut

Notes: Firm's exit probability of 6.18 percent. See Appendix 3.5.1 for details on the baseline parameterization of the model.

B.4.3 IRFs to Tax Shocks with Partial Congestion

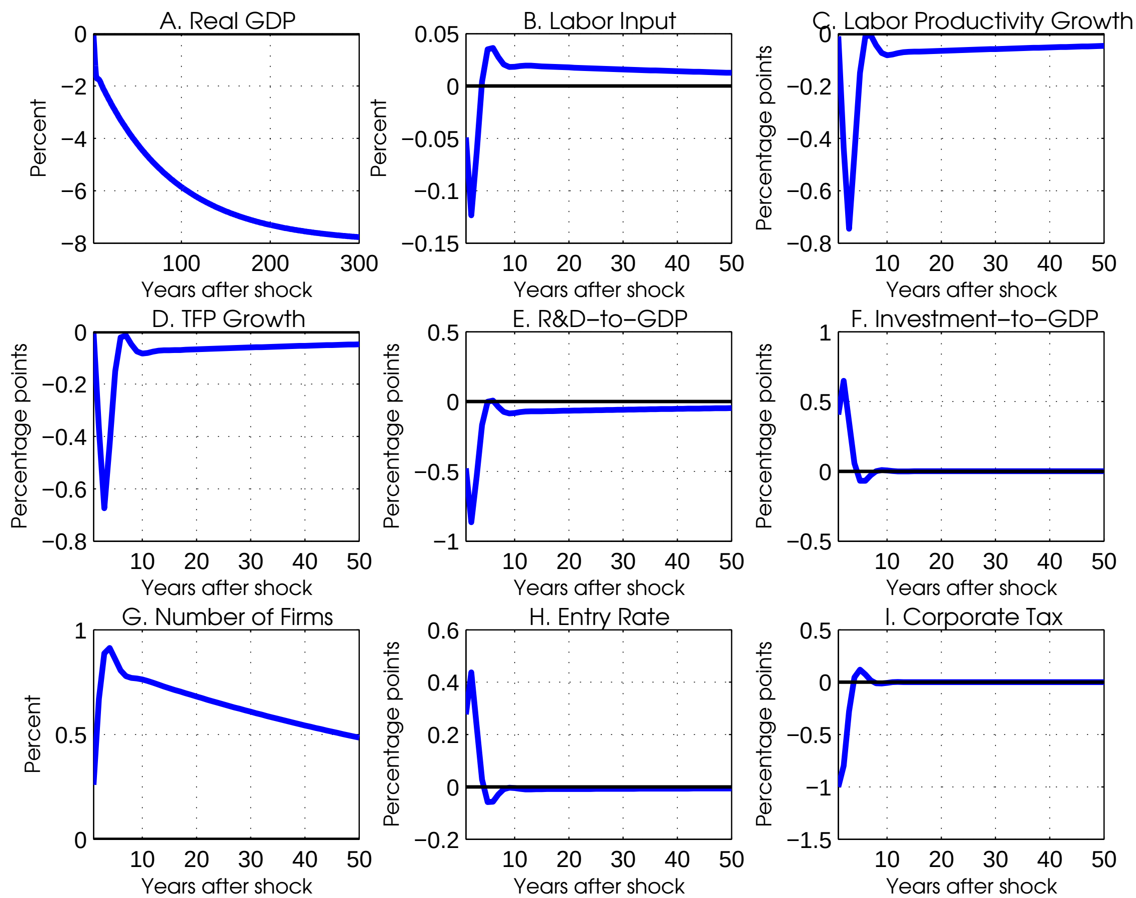

FIGURE C.4: Dynamic Response to a Corporate Tax Cut

Notes: Firm's exit probability of 6.18 percent. See Appendix 3.5.1 for details on the baseline parameterization of the model.

B.4.4 Steady-State Responses with a Fixed Number of Firms

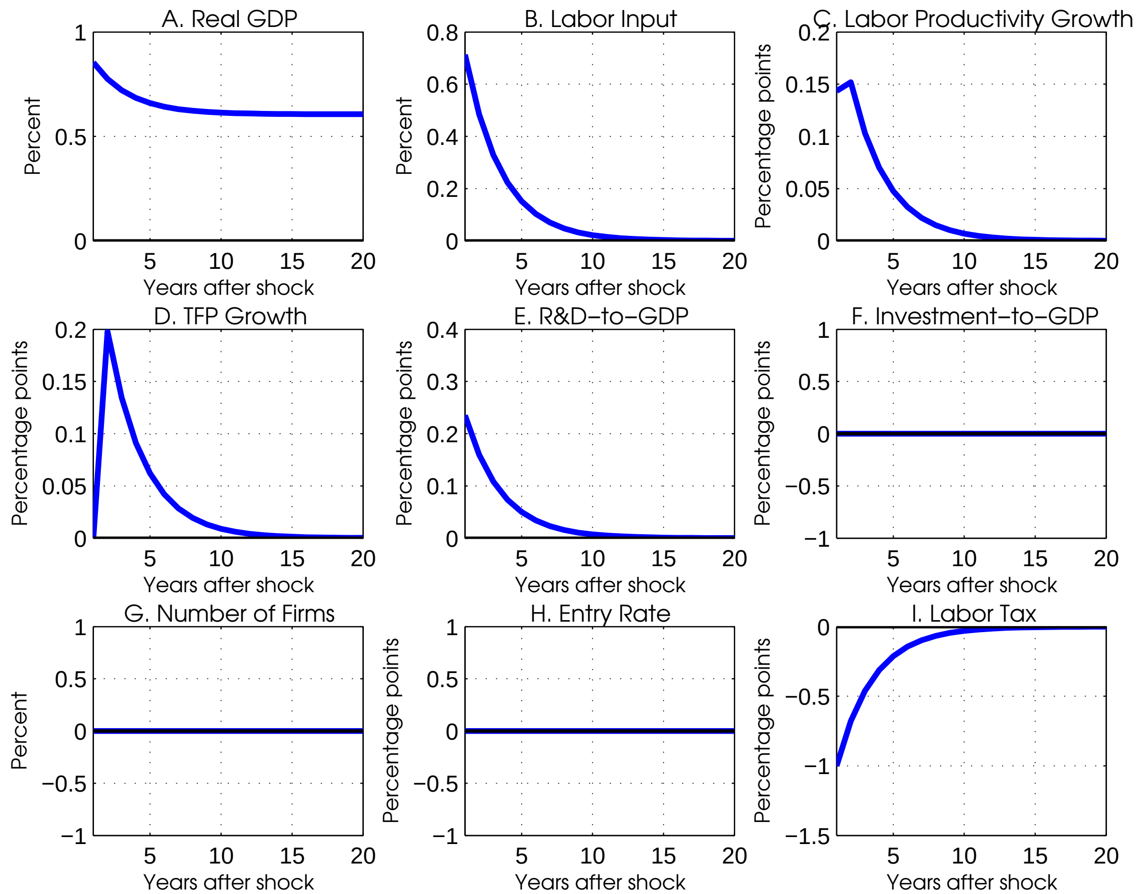

FIGURE C.5: Dynamic Response to a Labor Tax Cut

Notes: Fixed number of firms. See Appendix 3.5.1 for details on the baseline parameterization of the model.

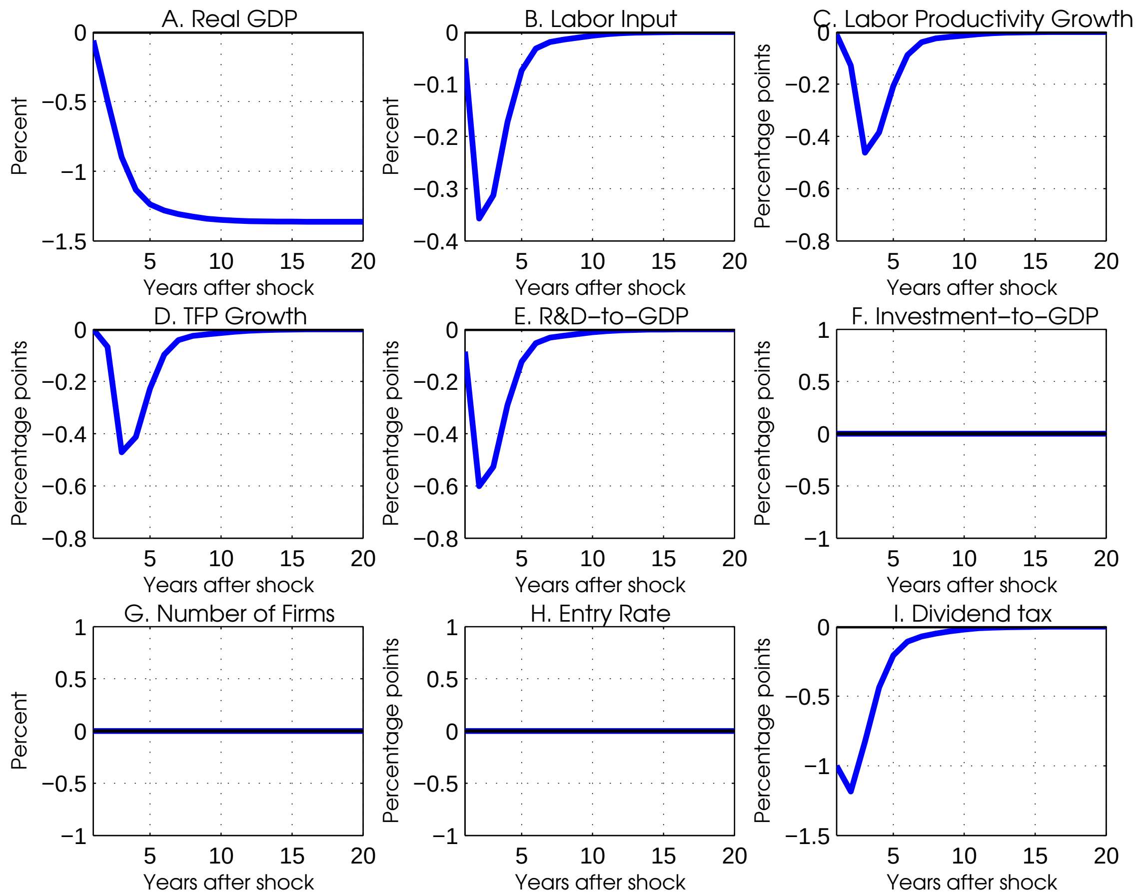

FIGURE C.6: Dynamic Response to a Dividend Tax Cut

Notes: Fixed number of firms. See Appendix 3.5.1 for details on the baseline parameterization of the model.

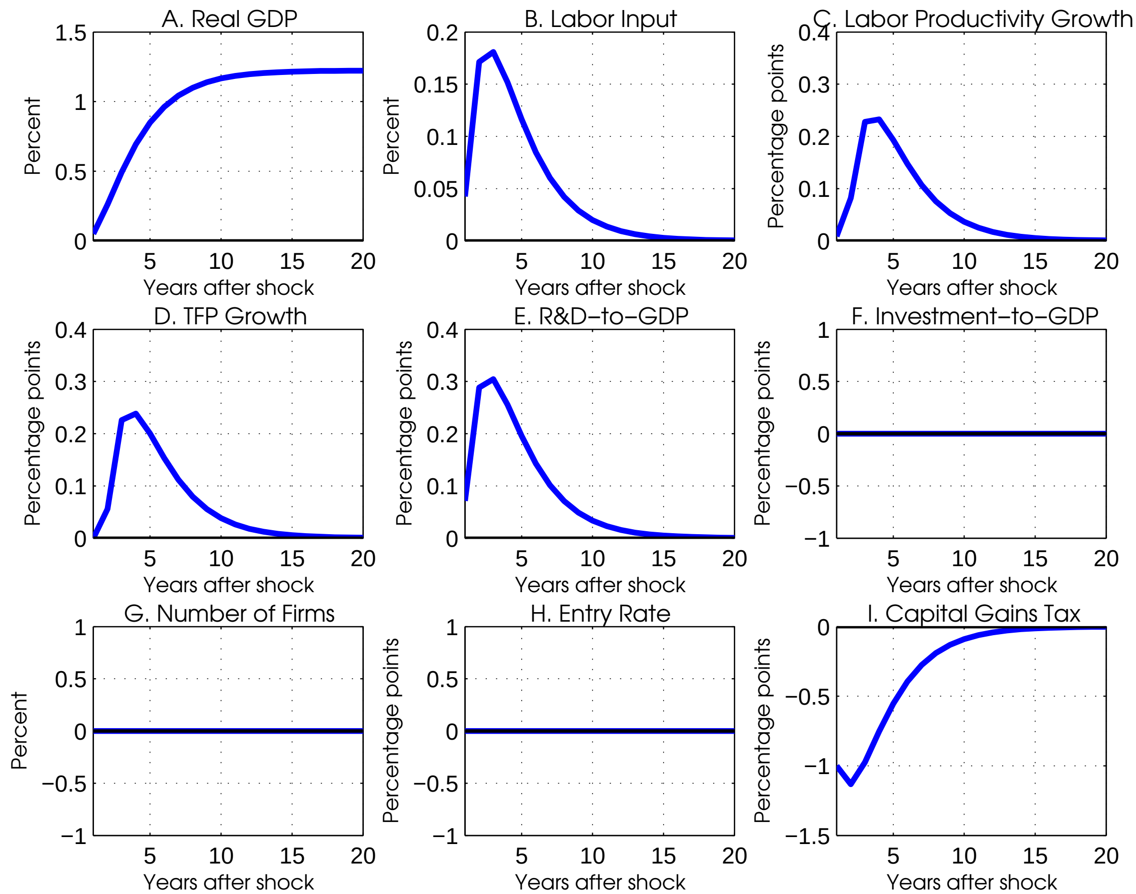

Figure C.7: Dynamic Response to a Capital Gains Tax Cut

Notes: Fixed number of firms. See Appendix 3.5.1 for details on the baseline parameterization of the model.

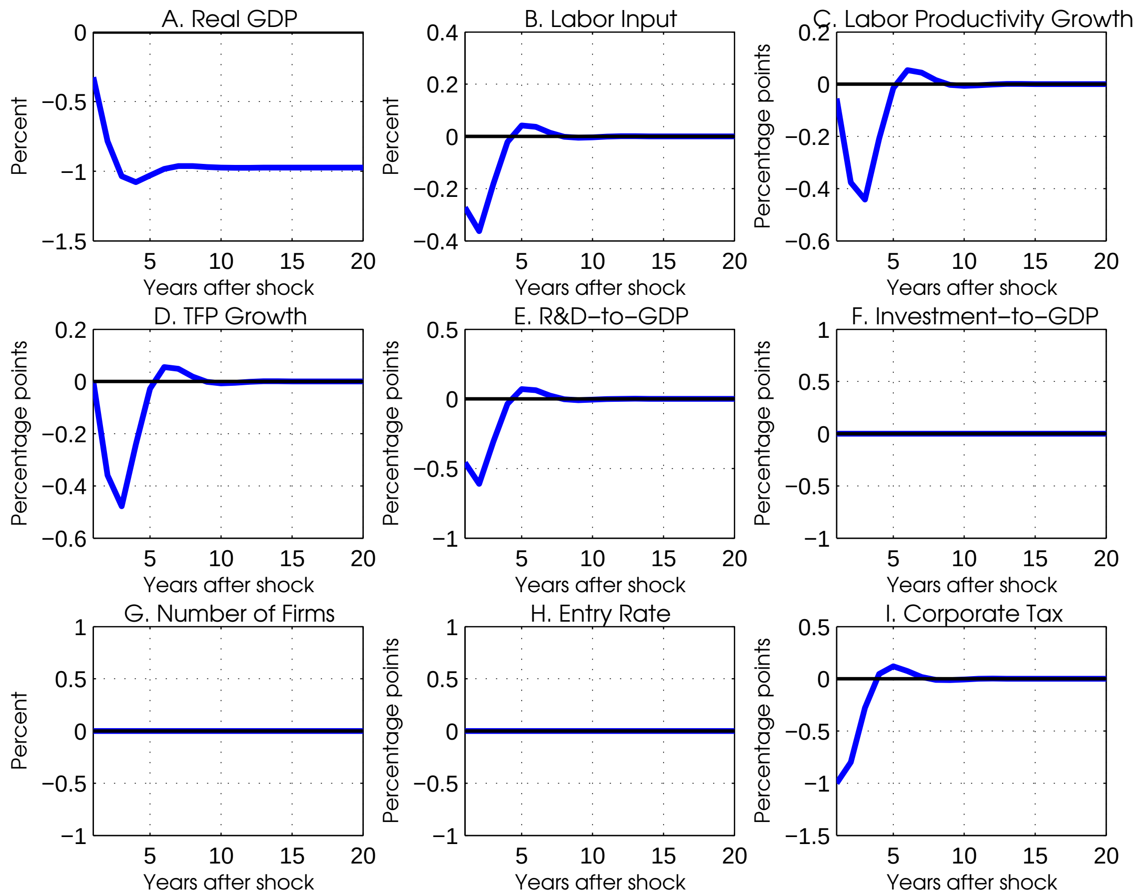

Figure C.8: Dynamic Response to a Corporate Tax Cut

Notes: Fixed number of firms. See Appendix 3.5.1 for details on the baseline parameterization of the model.

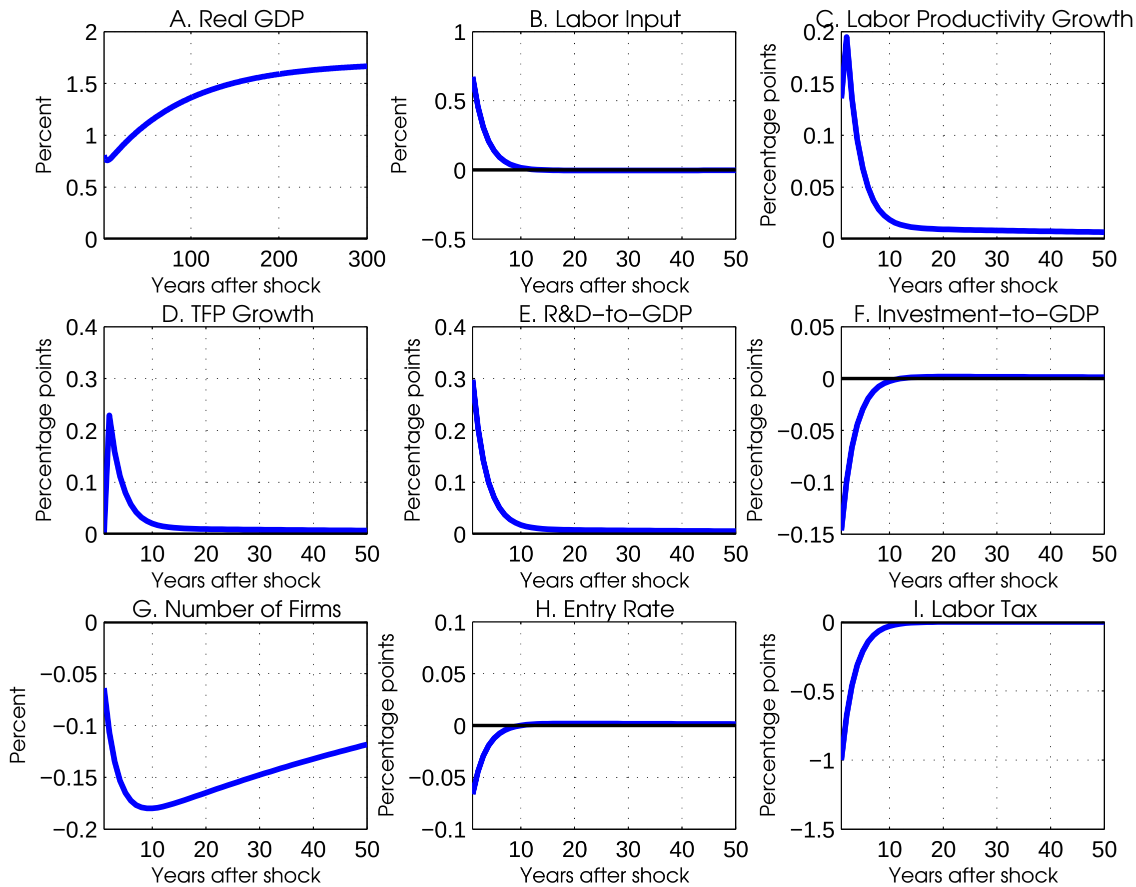

FIGURE C.9: Dynamic Response to a Labor Tax Cut

Notes: Labor congestion of 75 percent. See Appendix 3.5.1 for details on the baseline parameterization of the model.

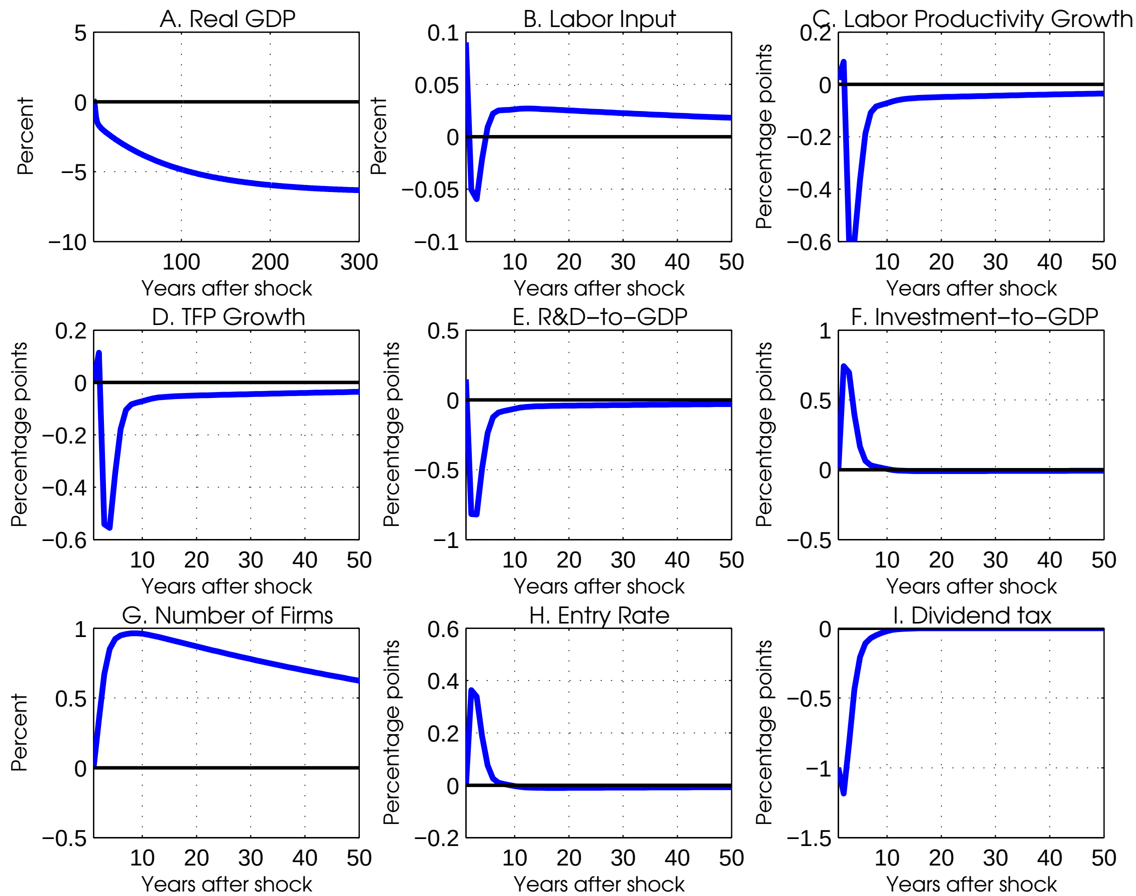

Figure C.10: Dynamic Response to a Dividend Tax Cut

Notes: Labor congestion of 75 percent. See Appendix 3.5.1 for details on the baseline parameterization of the model.

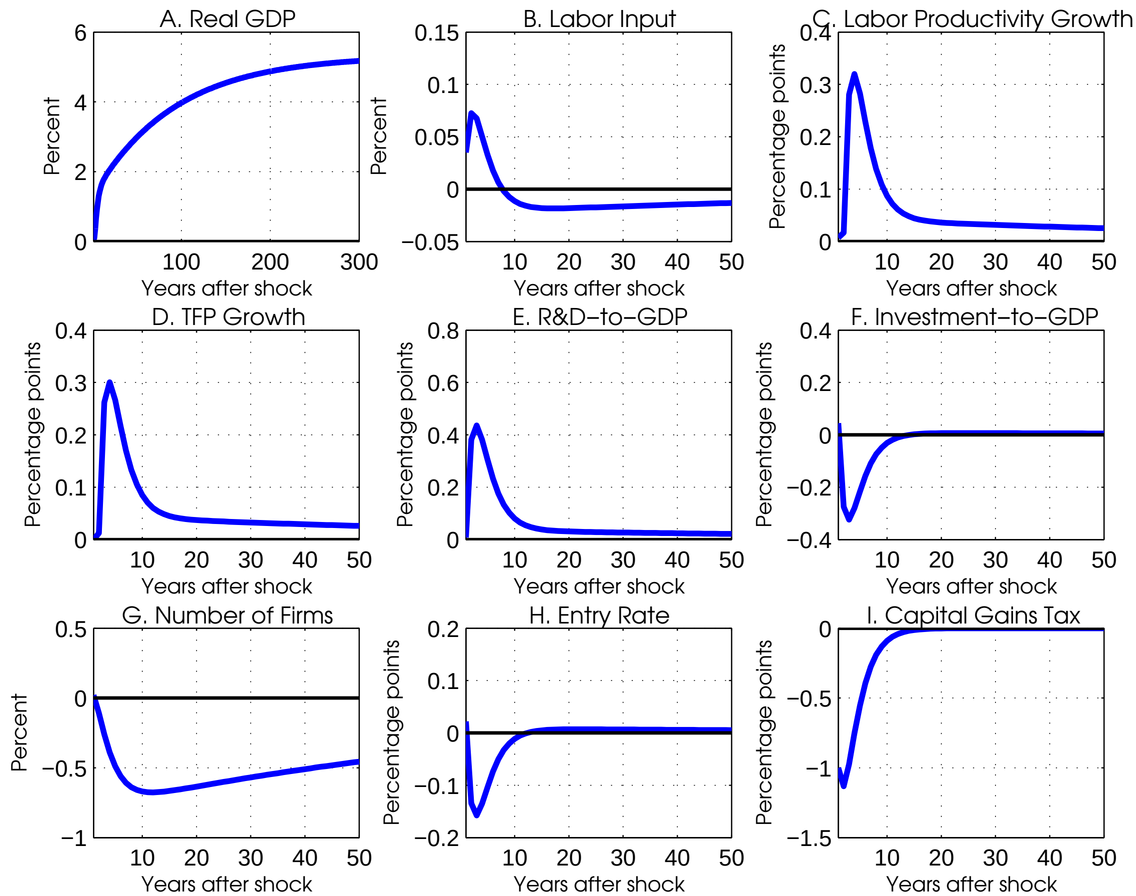

Figure C.11: Dynamic Response to a Capital Gains Tax Cut

Notes: Labor congestion of 75 percent. See Appendix 3.5.1 for details on the baseline parameterization of the model.

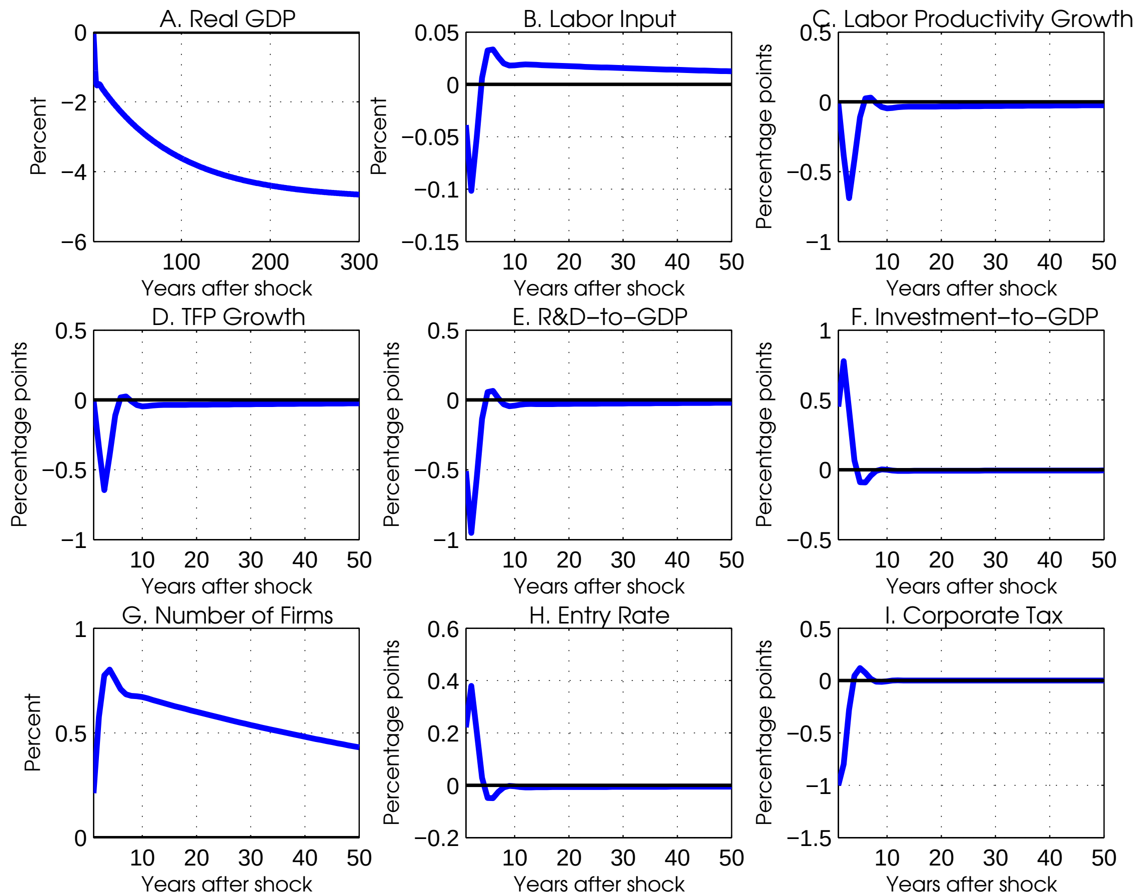

Figure C.12: Dynamic Response to a Corporate Tax Cut

Notes: Labor congestion of 75 percent. See Appendix 3.5.1 for details on the baseline parameterization of the model.

Table C.1: Long-Run Responses to Permanent Tax Cuts with a Fixed Number of Firms

	old steady-state	new steady-state (1 pp tax cut)				
		$\tau^d \downarrow$	$\tau^v \downarrow$	$\tau^\pi \downarrow$	$\tau^c \downarrow$	$\tau^l \downarrow$
A. Unitary Frisch elasticity of labor supply:						
Real GDP/TFP growth	2%	2%	2.05%	2%	2.02%	2.02%
R&D-to-GDP ratio	2.6%	2.6%	2.66%	2.6%	2.61%	2.61%
B. Labor indivisibility:						
Real GDP/TFP growth	2%	2%	2.05%	2%	2.03%	2.04%
R&D-to-GDP ratio	2.6%	2.6%	2.66%	2.6%	2.62%	2.62%

Notes: 1 percentage point (pp) tax cut from steady-state value. In panel A, a unitary Frisch elasticity of labor supply is pinned down by setting $\vartheta = 1$. In panel B, we set $\vartheta = 0$ for the labor indivisibility case. In both panels, we re-calibrate the disutility of work parameter γ such that the steady-state target of time spent at work of 0.277 is achieved: $\gamma = 8.15$ for the parametrization $\vartheta = 1$ in panel A, whereas $\gamma = 2.26$ for $\vartheta = 0$ in panel B. See Section 3.5.1 for further details on the baseline parametrization of the model.

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