Aggregate Implications of Innovation Policy

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Abstract

We examine the quantitative impact of changes in innovative investment by firms on growth in aggregate productivity and output in a model that nests several of the canonical models in the literature. We isolate two statistics that play a key role in shaping the model’s predicted response of aggregate productivity, output, and welfare to a policy-induced change in the innovation intensity of the economy. Given estimates of these statistics, we find that there is only modest scope for increasing aggregate productivity and output over a 20-year horizon with uniform subsidies to firms’ investments in innovation of a reasonable magnitude, but the welfare gains from such a subsidy can be substantial.

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1 Introduction

Firms’ investments in innovation are large relative to GDP and are likely an important factor in accounting for economic growth over time.\textsuperscript{1} Many OECD countries use taxes and subsidies to encourage these investments in the hope of stimulating economic growth.\textsuperscript{2} But what impact should we expect changes in firms’ investments in innovation induced by changes in innovation subsidies to have on economic growth at various time horizons? What are the welfare implications of subsidy-induced changes in firms’ investments in innovation? And what would be the fiscal cost of such subsidies?

We examine these questions in a model that nests some of the canonical models of the interaction of firms’ investments in innovation and aggregate productivity growth that have been developed over the past several decades. Our first contribution is to frame the quantitative answers to these questions in terms of a few sufficient statistics that apply across a broad class of models in the literature. Our second contribution is to measure these sufficient statistics, drawing on both available estimates in the literature and our own measurements.

Equipped with estimates of these statistics, we find that there is only modest scope for increasing aggregate productivity and output over a 20 year horizon with uniform subsidies to firms’ investments in innovation of a reasonable magnitude (the fiscal cost of the subsidies we consider are on the order of one percent of aggregate output annually). The magnitude of the model-implied movements in aggregate productivity and output that result over a 20 year horizon from such an increase in innovation subsidies would be difficult to distinguish from normal business cycle fluctuations in these variables. In contrast, we find that the welfare gains from this change in subsidies can be substantial because changes in innovation subsidies can have a large cumulative impact on aggregate productivity and output over very long horizons.

We conduct our assessment of the aggregate implications of innovation policies in a framework that allows for consistent comparisons of the quantitative predictions of a range of models. The model we use extends the model of firm dynamics in Garcia-

\textsuperscript{1}There is a wide range of estimates of the scale of firms’ investments in innovation. In the U.S. National Income and Product Accounts as revised in 2013, investments in intellectual property products in the non-financial corporate sector were 6.1% of value added in that sector averaged over the period 1990-2014 (see section 6 for additional details). Of that amount, roughly half was private research and development. Corrado et al. (2005) and Corrado et al. (2009) propose a broader measure of firms’ investments in innovation, which includes non-scientific R&D, brand equity, firm specific resources, and business investment in computerized information. These broader investments in innovation accounted for roughly 13% of non-farm output in the U.S. in 2005.

Macia et al. (2016). This model includes innovation by entering firms and innovations by incumbent firms to acquire products new to the firm (either new to society or “stolen” from other firms) and to improve firms’ existing products as drivers of firm dynamics and aggregate productivity growth. We extend this model to include a description of the technologies linking firms’ innovative investments and the arrival of those innovations that are left un-modeled in their paper. We make assumptions that allow for enough aggregation of investments across firms to allow us to characterize the model’s transition dynamics analytically and to make use of aggregate data in our measurement.

With these assumptions, our model nests the aggregate model of Jones (2002), Neo-Schumpeterian models based on the Quality Ladders framework which emphasize the role of business stealing by innovators — such as those described in Grossman and Helpman (1991b), Aghion and Howitt (1992), Klette and Kortum (2004) and Acemoglu and Cao (2015), and models based on the Expanding Varieties framework of Romer (1990) that emphasize the role of new product creation by innovators — such as those described in Grossman and Helpman (1991a), Luttmer (2007a), Atkeson and Burstein (2010), and Luttmer (2011). As described in Aghion et al. (2013), these are influential models that link micro data on firm dynamics to incumbent and entrant firms’ investments in innovation and, in the aggregate, to economic growth in a tractable manner.

To make our first contribution, we develop simple analytical results characterizing the cumulative impulse responses of the logarithm of aggregate productivity and output with respect to a policy-induced change in the innovation intensity of the economy as measured by the ratio of firms’ spending on innovation relative to output. Given other standard parameters, the dynamics of aggregate productivity and output can be summarized, up to a first order approximation, by two sufficient statistics: the impact elasticity of aggregate productivity growth with respect to an increase in aggregate real innovative investment, which we denote by $\Theta$, and the degree of intertemporal knowledge spillovers in research, which we denote by $\phi$. Not only do these sufficient statistics determine the model’s positive implications for the dynamics of aggregate productivity and output in response to a policy-induced change in the allocation of labor to research, but they also play a key role in determining the model’s normative implications for the welfare impact of changes in innovation policy. We also present analytical results for the fiscal cost in the long run of innovation subsidies required to implement a given permanent change in the innovation intensity of the economy.

To make our second contribution, we use our model to measure one of these sufficient statistics — the impact elasticity $\Theta$ of aggregate productivity growth with respect to a policy-induced change in aggregate real innovative investment. In our model, in response
to a proportional change in innovation subsidies for all types of innovative investment by firms, the elasticity $\Theta$ is bounded above by the ratio of the contribution of the innovative investments of entering firms to trend productivity growth, relative to the fraction of aggregate expenditure on innovative investment undertaken by entering firms.

In our quantitative analysis we use estimates of the contribution of innovative investments of entering firms to trend productivity growth presented in Akcigit and Kerr (2017) and Garcia-Macia et al. (2016) We also develop a simple method for using data on firm dynamics and the value of intangible capital in firms to infer the (unmeasured) share of aggregate innovative investment undertaken by entering firms. Our measurement of the value of intangible capital in firms follows the work of Hall (2003), and McGrattan and Prescott (2005a, Forthcoming), and others. Finally, we rely on the work of Jones (2002), Fernald and Jones (2014), and Bloom et al. (2017) for estimates of intertemporal knowledge spillovers.

While in our measurement we focus on the impact of proportional changes in innovation subsidies for all types of innovation by firms, in this paper we also derive analytical results regarding the impact of more general changes in innovation policies that might favor one type of innovative investment by firms over another on the dynamics of aggregate productivity and output. Using these results for practical analysis of these more general changes in policies requires measurement of incumbent firms’ elasticity of innovative investment with respect to specific policy changes, which we leave for future research. These analytic results are related to a growing literature examining the possibility that growth could be stimulated by using policy to reallocate innovative investment across firms without increasing aggregate real innovative investment (e.g. Acemoglu et al. 2013, Peters 2013, and Lentz and Mortensen 2014).

Finally, our paper is related to a very large literature that uses a straightforward extension of the standard growth model to measure the contribution of firms’ investments in intangible capital to the growth of aggregate productivity and output. One feature that distinguishes our framework form this prior literature is that, in our framework, there is no obvious aggregate intangible capital stock. More important, our model allows for a large gap between the social and the private returns to firms’ investments in innovation. This gap between private and social returns to innovation arises due to external increasing returns at the aggregate level of the economy (from love for variety), business stealing

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in firms’ innovations, and intertemporal technological spillovers across firms as current innovative investments impact the cost of future innovation. These features of our modeling framework require us to develop new methods for conducting our measurement of our key sufficient statistics.

The paper is organized as follows. In Section 2, we introduce a simple version of the model that includes only innovative investment by entering firms. In Section 3, we introduce our two sufficient statistics and use them to characterize analytically, up to a first order approximation, our model’s positive and normative implications for the equilibrium dynamics of aggregate productivity and output resulting from a subsidy-induced change in the investments in innovation by entering firms. In Section 4 we introduce innovative investment by incumbent firms into the model, and in Section 5 we present the assumptions needed to extend our analytical result from Section 3 to our full model. In Section 6 we outline the procedure and data we use to conduct our measurement. In Section 7 we present our quantitative results. In Section 8, we conclude. A full definition of equilibrium in our model is given in Appendix A. All proofs are given in Appendix B. A complete description of our measurement procedure is given in Appendix C.

2 Model

In this section we describe the environment and then present equilibrium conditions that we use when deriving our analytic results in Section 3. We focus here on a simple version of the model in which only entering firms engage in innovative investment. After developing our analytical results in this simplified framework, we show the conditions under which these results extend to version of the model in which both entering and incumbent firms engage in innovative activities in Sections 4 and 5.

2.1 Environment

Time is discrete and labeled \( t = 0, 1, 2, \ldots \). There are two final goods, the first of which we call the consumption good and the second of which we call the research good.

Output of the consumption good, denoted by \( Y_t \), is used for two purposes: as consumption by the representative household, \( C_t \), and as gross investment in physical (tangible) capital \( K_{t+1} \). The resource constraint for the final consumption good is given by

\[
Y_t = C_t + K_{t+1} - (1 - d_k) K_t,
\]
where $K_t$ denotes the aggregate physical capital stock and $d_k$ denotes the depreciation rate of physical capital. In what follows, we refer to $Y_t$ as aggregate output.

The representative household has preferences over consumption per capita $C_t/L_t$ given by

$$\sum_{t=0}^{\infty} \frac{\beta^t}{1-\eta} L_t(C_t/L_t)^{1-\eta},$$

with $\beta \leq 1$, and $\eta > 0$. Here $L_t$ denotes the population which grows at an exogenous rate $\bar{g}_L$.

**The Consumption Good** The consumption good $Y_t$ is produced as a constant elasticity of substitution (CES) aggregate of the output of a continuum of differentiated intermediate goods. At each date $t$, the technology with which any particular intermediate good can be produced is summarized by its productivity index $z$. Production of an intermediate good with productivity index $z$ is carried out with physical capital, $k$, and labor, $l$, according to

$$y_t(z) = \exp(z)k_t(z)^{\alpha}l_t(z)^{1-\alpha},$$

where $0 < \alpha < 1$. To simplify our notation, we assume that the support of $z$ is a countable grid with elements $z_n = n\Delta$ for the integers $n$. For each intermediate good that can be produced at time $t$, we refer to the technology with the highest value of $z$ on this grid available for producing this good as the frontier technology for producing this good.

Aggregate output is then given by the CES aggregator

$$Y_t = \left[ \sum_z y_t(z)^{1-(\rho-1)/\rho} M_t(z) \right]^{\rho/(\rho-1)},$$

where $y_t(z)$ denotes the output of each intermediate good with productivity index $z$, and $M_t(z)$ is the measure of intermediate goods with frontier technology indexed by $z$ at time $t$.

We let $L_{pt} = \sum_z l_t(z) M_t(z)$ denote the aggregate amount of labor engaged in current production of intermediate goods at time $t$. Labor can be allocated to current production of intermediate goods, $L_{pt}$, and to production of the research good, $L_{rt}$, subject to the labor market clearing condition $L_{pt} + L_{rt} = L_t$, where total labor $L_t$ is inelastically supplied by households. The resource constraint for physical capital requires that $K_t = \sum_z k_t(z) M_t(z)$.

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Under the assumption of a CES aggregator, the productivity index $z$ for intermediate goods can be reinterpreted as a measure of product quality (so that firms innovate to improve the quality of products rather than to increase their productivity), without changing the results in this paper.
We assume that in each period $t$, physical capital and labor are freely mobile across intermediate goods producing firms and that the markup $\mu \geq 1$ of price over marginal cost charged by intermediate goods producers is constant across intermediate goods and over time. Let

$$s_t(z) \equiv \frac{\exp((\rho - 1)z)}{Z_t^{\rho-1}}$$

where $Z_t$ is given by

$$Z_t = \left[ \sum_z \exp((\rho - 1)z)M_t(z) \right]^{1/(\rho-1)}.$$  

We refer to the term $s_t(z)$ as the size of an intermediate good with index $z$ at time $t$ since in equilibrium this term is equal to the share of revenues and inputs allocated to an intermediate good with productivity index $z$. In equilibrium, aggregate output can be written as

$$Y_t = Z_t (K_t)^\alpha (L_{pt})^{1-\alpha}.$$  

Hence, we refer to $Z_t$ as aggregate productivity at time $t$.\footnote{In general, this model-based measure of aggregate productivity, $Z_t$, does not correspond to measured TFP, which is given by $\text{TFP}_t = \frac{\text{GDP}_t}{\left( K_t^\phi L_t^{1-\tilde{\alpha}} \right) }$, where the definition of GDP depends on the measurement standard for expenditures on innovative investment being used (e.g. the definition of output of the final consumption good $Y_t$ in equation (1) corresponds to the pre-2013 measurement of GDP, which did not include expenditures on innovative investment), and $1 - \tilde{\alpha}$ denotes the share of labor compensation in measured GDP. We can use our analytic comparative statics below to construct alternative measures of TFP and GDP.} We refer to $M_t = \sum_z M_t(z)$ as the total measure of products available, and to the ratio $Z_t^{\rho-1}/M_t$ as the average productivity index of existing intermediate goods (specifically, the average of $\exp((\rho - 1)z)$ across intermediate goods).

The research good The second final good in this economy, which we call the research good, is the input used for innovative investment by firms. Production of the research good is carried out using research labor $L_{rt} = L_t - L_{pt}$ according to\footnote{Here, for simplicity, we assume that the research good is produced entirely with labor. In Appendix D.2 we consider an extension in which research production uses both labor and consumption good, as in the lab-equipment model of Rivera-Batiz and Romer (1991).}

$$Y_{rt} = A_{rt} Z_t^{\phi-1} L_{rt}.$$  

Here $A_{rt}$ represents the stock of freely available scientific progress which grows at an exogenous rate $\bar{g}_A$.\footnote{It is common in the theoretical literature on economic growth with innovating firms to assume that all productivity growth is driven entirely by firms’ expenditures on R&D (Griliches 1979, p. 93). As noted} The term $Z_t^{\phi-1}$ with $\phi \leq 1$ reflects intertemporal knowledge spillovers in
the production of the research good as in the model of Jones (2002). Using the language of Bloom et al. (2017), \( A_{rt}Z_t^{\phi-1} \) denotes the productivity with which research labor \( L_{rt} \) translates into a real flow of “ideas” \( Y_{rt} \) available to be applied to innovative investment. Exogenous scientific progress drives up research productivity over time. If \( \phi < 1 \), then increases in the level of aggregate productivity \( Z_t \) reduce research productivity in the sense that “ideas become harder to find”. Because the impact of advances in \( Z_t \) on the research productivity is external to any particular firm, we call it a spillover. The parameter \( \phi \) indexes the extent of this spillover.

An intermediate goods producing firm in our model is an organization that owns the exclusive rights to use the frontier technology for producing one or more intermediate goods. Aggregate productivity in our model grows as a result of innovations by intermediate goods producing firms that increase the average productivity index \( z \) of frontier technologies available for existing intermediate goods and/or increase the total measure of intermediate goods available. These innovations arrive at rates determined by the investments in innovation undertaken by these firms.

We refer to those firms producing intermediate goods at \( t \) that also produced at \( t - 1 \) as incumbent firms. We refer to those firms at \( t \) are new (and hence did not produce intermediate goods at \( t - 1 \)) as entering firms. In our first simplified presentation of our model, we assume that only entering firms engage in innovative investment. For incumbent firms, there are no innovations on the products that they produce. In addition, an exogenous fraction \( \delta_0 \) of the products produced by incumbent firms exit each period. In section 4 we extend our model to consider the aggregate implications of innovative investment when such investment is undertaken both by incumbent and entering firms.

2.2 Innovative Investment by Entering Firms

Entering firms purchase units of the research good to invest in obtaining the frontier technology to produce an intermediate good that is new to that entering firm. Let \( M_{et+1} \) denote the measure of entering firms engaging in innovative investment at \( t \). Each of these \( M_{et+1} \) entering firms at \( t \) acquires at the start of period \( t + 1 \) a frontier technology to produce an intermediate good that is new to this entering firm with some productivity index

in Corrado et al. (2011), this view ignores the productivity-enhancing effects of public infrastructure, the climate for business formation, and the fact that private R&D is not all there is to innovation. We capture all of these other productivity enhancing effects with \( A_r \). Relatedly, Akcigit et al. (2013) consider a growth model that distinguishes between basic and applied research and introduces a public research sector. As we discuss below, the only role served by the exogenous growth of scientific progress \( A_{rt} \) in our analysis is that, by adjusting the parameter \( g_{A_r} \), we can target a given baseline growth rate in the balanced growth path as we vary the parameter \( \phi \).
With probability \( \delta_e \), this productivity index \( z' \) drawn by the entrant at \( t + 1 \) is associated with an intermediate good that was already being produced by an incumbent firm at \( t \), but with a lower productivity index. Since identical intermediate goods are perfect substitutes in the production of the final consumption good, competition in the product market between the entering firm and the previous incumbent producer of this intermediate good implies that the previous incumbent producer ceases production of the good. In this case, the innovative investment by the entering firm does not result in a net increase in the total measure of products available \( M_{t+1} \). Instead, it only results in a positive increment to the average productivity index across existing products. As is common in the literature, we say that this intermediate good that is new to the entering firm was stolen from an incumbent firm.

With the complementary probability \( 1 - \delta_e \), this technology allows this entering firm to produce an intermediate good that is new to society as a whole in the sense that it has elasticity of substitution in demand with all other existing intermediate goods determined by \( \rho \). In this case, the innovative investment by the entering firm results in a net increase in the total measure of products available \( M_{t+1} \). The parameter \( \delta_e \) thus indexes the extent of business stealing by entering firms.

The productivity index \( z' \) for stolen products in entering firms is drawn in a manner similar to that in Klette and Kortum (2004) and other standard Quality Ladders type models. Specifically, we assume that stolen products in entering firms at \( t + 1 \) have a productivity index \( z' \) drawn from a distribution such that the expected value of the term \( \exp((\rho - 1)z') \) is equal to \( E \exp((\rho - 1)z') = \eta_{es}Z_{t}^{\rho-1} / M_t \), with \( \eta_{es} > 1 \).

The productivity index \( z' \) for products that are new to society in entering firms is drawn in a manner similar to that in Luttmer (2007a). Specifically, we assume that new products in entering firms at \( t + 1 \) have a productivity index \( z' \) drawn from a distribution such that the expected value of the term \( \exp((\rho - 1)z') \) is equal to \( E \exp((\rho - 1)z') = \eta_{en}Z_{t}^{\rho-1} / M_t \), with \( \eta_{en} > 0 \).

These assumptions imply that the average value of \( \exp((\rho - 1)z') \) across all products produced by entering firms at \( t + 1 \) is given by \( E \exp((\rho - 1)z') = \eta_{e}Z_{t}^{\rho-1} / M_t \), where \( \eta_{e} = \delta_e \eta_{es} + (1 - \delta_e)\eta_{en} \).

Now consider the innovative investment required of entering firms. The investment required at time \( t \) is impacted by aggregate spillovers. We specify these spillovers to ensure that, on a balanced growth path with growth in both the average productivity of

\[\eta_{es} = \exp((\rho - 1)\Delta_s), \text{ where } \Delta_s > 0 \text{ denotes the percentage improvement in productivity of stolen products.}\]
products $Z_t^{\rho-1}/M_t$ and in the total measure of products $M_t$, aggregate innovative investment by entering firms is constant over time. Specifically, an entrant at time $t$ spends $1/M_t$ units of the research good to launch a new firm at $t+1$ with one product.\(^9\) If there are a total of $M_{et+1}$ entering firms at time $t$, then they spend in total $x_{et} = M_{et+1}/M_t$ units of the research good and acquire $M_{et+1}$ new products at $t+1$. The resource constraint for the research good is $x_{et} = Y_{rt}$.

### 2.3 Dynamics of aggregate productivity

We now describe the evolution of the total measure of products available, $M_t$, and aggregate productivity, $Z_t$, that results from innovative investment by entering firms.

The evolution of the total measure of products available is governed by the exit by incumbent firms from production of existing intermediate goods and the entry into production of intermediate goods by entering firms. Incumbent firms producing $M_t$ products at $t$ cease production of these goods for two reasons. First, a fraction $\delta_0$ of those products cease production exogenously. Second, a fraction $\delta_e M_{et+1}/M_t = \delta_e x_{et}$ of these products cease production due to the entry of a lower cost alternative produced by an entering firm (a.k.a. business stealing). Under these assumptions, the dynamics of the total measure of products is given by

$$M_{t+1} = [1 - \delta_0 + (1 - \delta_e) x_{et}] M_t. \quad (9)$$

The evolution of aggregate productivity $Z_t$ from $t$ to $t+1$ is as follows. A measure $M_{et+1}$ of products produced at $t+1$ are produced in newly entered firms and have average productivity index $\mathbb{E} \exp((\rho - 1)z') = \eta_e Z_{t+1}^{\rho-1}/M_t$. The complementary measure $M_{t+1} - M_{et+1}$ of products are produced in incumbent firms that do not experience innovations and hence have average productivity index $\mathbb{E} \exp((\rho - 1)z') = Z_{t}^{\rho-1}/M_t$ equal to the average productivity index of intermediate goods at date $t$. Thus, aggregate productivity at $t+1$ satisfies

$$Z_{t+1}^{\rho-1} = [M_{t+1} - M_{et+1} + \eta_e M_{et+1}] \frac{Z_{t}^{\rho-1}}{M_t}. \quad (9)$$

This observation together with equations $M_{et+1} = x_{et}M_t$, (9), and the resource constraint for the research good, $x_{et} = Y_{rt}$, imply that the dynamics of aggregate productivity as a

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\(^9\)The spillover we assume here from the total measure of products $M_t$ to the cost of entry follows Ace-moglu (2009) Chapter 13.4. Our results are unchanged if we introduce an additional parameter $\bar{y}_e$ such that entry costs are given by $\bar{y}_e/M_t$ (we have imposed $\bar{y}_e = 1$).
function of innovative investment are summarized by

\[ g_{Zt} = \log(Z_{t+1}) - \log(Z_t) = G(Y_{rt}) \]  

(10)

where

\[ G(Y_r) = \frac{1}{\rho - 1} \log \left( 1 - \delta_0 + (\eta_e - \delta_e)Y_r \right). \]  

(11)

We define the social depreciation rate of innovation expenditures as the growth rate of aggregate productivity if all firms were to set their use of the research good to zero, i.e. \( G^0 \equiv G(0) \).

### 2.4 Policies

In what follows, we consider our model’s quantitative implications for the response of aggregate productivity growth at various horizons to a change in innovation subsidies. The innovation subsidies that we consider in our simple model are subsidies \( \tau_{et} \) to entering firms’ expenditures on innovation. Specifically, a firm that purchases \( x \) units of the research good at time \( t \) pays \( P_{rt}x \) to a research good producer for that purchase and then receives a rebate of \( \tau_{et}P_{rt}x \) from the government. Changes in innovation subsidies do not directly affect the form of functions \( Z \) and \( G \) defined in equations (6) and (11), but do result in changes in the equilibrium innovative investment by firms and hence to changes in aggregate productivity growth and in the time path for all other macroeconomic variables.

### 2.5 Macroeconomic equilibrium conditions

We assume that, at \( t = 0 \), the representative household owns the incumbent intermediate goods producing firms and the physical capital stock. It faces a sequence of budget constraints given by

\[ C_t + K_{t+1} - (1 - d_k)K_t = R_{kt}K_t + W_tL_t + D_t - (1 - \tau_{et})P_{rt}x_{et} - E_t, \]  

(12)

in each period \( t \), where \( W_t, R_{kt}, D_t, (1 - \tau_{et})P_{rt}x_{et} \), and \( E_t \) denote the economy-wide wage (assuming that labor is freely mobile across production of intermediate goods and the research good), rental rate of physical capital, aggregate dividends paid by incumbent in-

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\(^{10}\)Our definition of the social depreciation of innovation is analogous to defining the depreciation of physical capital as \( \log(1 - d_k) \), that is, as equal to the value of \( \log K_{t+1} - \log K_t \) that would obtain if gross physical investment were zero.
termediate good producing firms, households’ expenditures on creating new firms net of subsidies to innovation, and aggregate fiscal expenditures on policies (which are financed by lump-sum taxes collected from the representative household), respectively.

Revenues from the sale of the final consumption good are split into payments to factors of production as follows. A share \((\mu - 1) / \mu\) of revenues from the sale of the final consumption good accrues to variable profits from intermediate goods production, so that aggregate dividends are given by \(D_t = \frac{(\mu - 1)}{\mu} Y_t\). Of the remaining revenues, a share \(\alpha / \mu\) is paid to physical capital, \(R_{kt}K_t = \frac{\alpha}{\mu} Y_t\), and a share \((1 - \alpha) / \mu\) is paid as wages to production labor, \(W_tL_{pt} = \frac{(1 - \alpha)}{\mu} Y_t\).

Production of the research good is undertaken by competitive firms that do not internalize the intertemporal knowledge spillover from innovation in equation (8). The price of the research good, \(P_{rt}\), is equal to its marginal cost,

\[
P_{rt} = \frac{Z_t^{1-\phi}}{A_{rt}} W_t.
\]

Given that the research good is priced at marginal cost, then wage payments to research labor equal revenues from production of the research good: \(W_tL_{rt} = P_{rt} Y_{rt}\).

We define the innovation intensity of the economy, \(i_{rt}\), as the ratio of innovation expenditure \(P_{rt} Y_{rt}\) to output \(Y_t\), that is \(i_{rt} \equiv P_{rt} Y_{rt} / Y_t\). Using the factor shares above and the assumption that labor is freely mobile between production and research, the ratio of production labor to total labor and the ratio of research labor to total labor, \(l_{pt} \equiv L_{pt} / L_t\) and \(l_{rt} \equiv L_{rt} / L_t\), are related to the innovation intensity of the economy \(i_{rt}\) by

\[
l_{rt} = \frac{i_{rt}}{i_{rt} + \frac{(1 - \alpha)}{\mu}} \text{ and } l_{pt} = 1 - l_{rt},
\]

where the term \((1 - \alpha) / \mu\) is the share of labor compensation in output.\(^{11}\)

\(^{11}\)In Appendix D.1 we present an extension in which labor is imperfectly substitutable between production and research as in Jaimovich and Rebelo (2012). The assumption of imperfect substitutability reduces the elasticity of the allocation of labor between production and research with respect to a policy-induced change in the innovation intensity of the economy, resulting in smaller responses of aggregate productivity and output to a given change in the innovation intensity of the economy relative to those in our baseline model. Assuming congestion in the production of the research good (i.e. in which case research labor in the production of the research good has an exponent less than one), as discussed in Jones (2005), has similar implications.
2.6 Balanced growth paths

To develop our analytical results, we consider the impact of changes in innovation policies on the macroeconomic dynamics of an economy that starts on an initial balanced growth path (BGP). We consider BGPs of the following form. Output of the final consumption good and the stock of physical capital both grow at a constant rate $\bar{g}_Y$ and aggregate productivity grows at a constant rate $\bar{g}_Z = (1 - \alpha)\bar{g}_Y$. The innovation intensity of the economy $i_{rt}$, the allocation of labor in production and research $l_{pt}$ and $l_{rt}$, and output of the research good $Y_{rt}$ all remain constant over time at the levels $\bar{i}_r$, $\bar{l}_p$, $\bar{l}_r$, and $\bar{Y}_r$, respectively.

In specifying the production function for the research good (8) and firms’ technology for innovative investment, we have followed Jones (2002) and Bloom et al. (2017) in choosing units such that it is possible to maintain a constant growth rate of aggregate productivity by investing a constant real amount $Y_r$ of the research good. In deriving our analytic results, we assume that such a BGP exists.

If $\phi < 1$, then our model is a semi-endogenous growth model with the growth rate along the BGP determined by the exogenous growth rate of scientific knowledge $\bar{g}_{Ar}$ and population $\bar{g}_L$ and other parameter values independent of innovation policies, as in Kortum (1997) and Jones (2002). In this case, it is not possible to have fully endogenous growth because such growth would require growth in innovation expenditure in excess of the growth rate of output. Ongoing balanced growth can occur only to the extent that exogenous scientific progress or population growth reduces the cost of further innovation as aggregate productivity $Z$ grows. Given the assumption that real research output is constant on a BGP, these BGP growth rates are given from equation (8) as $\bar{g}_Z = (\bar{g}_{Ar} + \bar{g}_L) / (1 - \phi)$.

If the knife-edged conditions $\phi = 1$ and $\bar{g}_{Ar} = \bar{g}_L = 0$ hold, then our model is an endogenous growth model with the growth rate along the BGP determined by firms’ investments in innovative activity, as in Grossman and Helpman (1991b) and Klette and Kortum (2004). As discussed in Section 5 of Jones (2005), the transition paths of the response of aggregate productivity and output to policy changes are continuous as $\phi$ approaches one and hence the quantitative implications of our model for the response of the level of aggregate productivity at any finite horizon to changes in innovation policies is continuous in this parameter.

In our applications, we calibrate the model parameters to match a given BGP per capita growth rate of output, $\bar{g}_Y$. Specifically, given a choice of $\bar{g}_Y$ and physical capital share in production of the final consumption good of $\alpha$, the growth rate of aggregate pro-

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12If $\phi > 1$, then our model does not have a BGP, as in this case, a constant innovation intensity of the economy leads to an acceleration of the innovation rate as aggregate productivity $Z$ grows.
ductivity in the BGP is \( \bar{g}_Z = (\bar{g}_Y - \bar{g}_L)(1 - \alpha) \). For a given choice of \( \phi \), we choose the growth rate of scientific knowledge consistent with this productivity growth rate, that is \( \bar{g}_{Ar} = (1 - \phi) \bar{g}_Z - \bar{g}_L \).

3 Analytical results with innovation by entrants only

In this section, we derive positive and normative analytical results regarding the aggregate impact of policy-driven changes in the innovation intensity of the economy in our simple model with innovation investments only by entering firms. We begin with positive results on the dynamics of aggregate productivity and output that result, up to a first-order approximation, from a policy-induced change in the time path of the innovation intensity of the economy. We then consider the model’s implications for the welfare gains to be had from a subsidy to innovative investment on the initial BGP and for the socially optimal innovation intensity of the economy. We conclude with a result regarding the long-run fiscal cost of the innovation subsidies required to induce firms to permanently raise the innovation intensity of the economy. In presenting our results, we focus on the semi-endogenous growth case \( \phi < 1 \). We comment briefly on the results that can be derived in the endogenous growth case \( \phi = 1 \). Proofs of all results are presented in Appendix B.

In framing the question of how policy-induced changes in the innovation intensity of the economy impact aggregate outcomes at different time horizons, we consider the following thought experiment. Consider an economy that is initially on a BGP with growth rate of aggregate productivity \( \bar{g}_Z \). On this initial BGP, the paths of aggregate productivity and output are given by \( \bar{Z}_t = \exp(t \bar{g}_Z) \bar{Z}_0 \) and \( \bar{Y}_t = \exp(t \bar{g}_Y) \bar{Y}_0 \) respectively. As a baseline policy experiment, consider a change in innovation subsidies on the initial BGP \( \tau_e \) to new innovation subsidies \( \{\tau'_e\} \) beginning in period \( t = 0 \) and continuing on for all \( t > 0 \). Assume that these new innovation policies converge to a constant value \( \bar{\tau}'_e \) and that the equilibrium corresponding to these policies also converges to a new BGP. The innovation intensity of the economy, the allocation of labor in production and research, and output of the research good on this new BGP are denoted by \( \bar{i}'_r, \bar{\bar{p}}'_r, \bar{l}'_r \) and \( \bar{Y}'_r \), respectively.

This policy experiment leads to some observed change in the equilibrium path of the innovation intensity of the economy \( \{i'_r\}_t=0^\infty \) different from the innovation intensity of the economy \( i_r \) on the original BGP. We seek to analytically approximate the resulting change in the equilibrium path of aggregate productivity and output relative to the initial BGP, \( \{\log Z'_t - \log \bar{Z}_t\}_t=1^\infty \) and \( \{\log Y'_t - \log \bar{Y}_t\}_t=0^\infty \), given a policy induced change in the path of
the innovation intensity of the economy \( \left\{ \log_i't - \log_i't \right\}_{t=0}^{\infty} \). Note that the initial level of aggregate productivity \( Z_0 = Z_0 \) is a state variable.

### 3.1 Productivity in the Long-Run

The following Proposition provides an expression for the long-run change in aggregate productivity that corresponds to a given permanent change in the innovation intensity of the economy.

**Proposition 1.** Consider a permanent change in innovation policies such that the economy converges to a new BGP with new innovation intensity \( \bar{i}'_r \) and corresponding new allocation of labor to research \( \bar{l}'_r \) given by equation (14) evaluated at \( \bar{i}'_r \). In the semi-endogenous growth case \( (\phi < 1) \), the gap in aggregate productivity between the initial and new BGP converges to

\[
\log \bar{Z}'_t - \log \bar{Z}_t = \frac{1}{1 - \phi} (\log \bar{l}'_r - \log \bar{l}_r).
\] (15)

Proposition 1 indicates that the impact over the long run of a policy-induced change in the innovation intensity of the economy is determined entirely by two features of the model: the parameter \( \phi \) indexing the extent of intertemporal knowledge spillovers, and (in equation 14) the share of labor compensation in output, \( (1 - \alpha) / \mu \).

The response in the long run of the level of aggregate productivity to a policy-induced change in the innovation intensity of the economy is very sensitive to the specification of intertemporal knowledge spillovers. For low values of \( \phi \), particularly for values less than zero such as those implied by the estimates of Fernald and Jones (2014), the long run change in log productivity is smaller than the change in the log of the innovation intensity of the economy since, in that case, \( 1/ (1 - \phi) < 1 \). For values of \( \phi \) close to one, the response in the long run of the level of aggregate productivity approaches infinity as the implications of the model converge to those of an endogenous growth model.

### 3.2 Productivity Transition Dynamics

We now consider features of the model that determine the transition dynamics of aggregate productivity in response to a policy-induced change in the innovation intensity of the economy. We use the notation

\[
\Theta \equiv \frac{dG(Y_r)}{dY_r} \bar{Y}_r.
\] (16)
where the derivative \( dG(Y_r) / dY_r \) is evaluated at \( Y_r = \bar{Y}_r \) on the initial BGP. Note that our assumptions that \( \eta_{es} > 1 \) and \( \eta_{en} > 0 \) imply that \( \eta_e = \delta \eta_{es} + (1 - \delta) \eta_{en} > \delta \). Thus, from equation (11), we have \( dG(Y_r) / dY_r > 0 \) and hence \( \Theta > 0 \).

With this notation, we have, to a first order approximation, the following relationship between real aggregate innovative investment and aggregate productivity growth

\[
\log Z'_{t+1} - \log Z'_t - g_Z \approx \Theta (\log Y'_{rt} - \log \bar{Y}_r).
\] (17)

Given this equation, we refer to this parameter \( \Theta \) as the impact elasticity of aggregate productivity with respect to a change in real innovative investment.

We can now characterize, up to a first order approximation, the transition dynamics of aggregate productivity with respect to a policy induced change in the innovation intensity of the economy with the following proposition.

**Proposition 2.** Suppose an economy is on an initial baseline BGP and, at time \( t = 0 \), a change in innovation policies induces a new path for the innovation intensity of the economy given by \( \{i'_r\}^{\infty}_{t=0} \). The new path for aggregate productivity \( \{Z'_t\}^{\infty}_{t=1} \) to a first-order approximation is given by

\[
\log Z'_{t+1} - \log Z'_t \approx \sum_{k=0}^{t} \Gamma_k \left( \log l'_r \text{ for } t, \log \bar{l}_r \text{ for } k \geq 0 \right),
\] (18)

where \( \Gamma_0 \) denotes the elasticity of aggregate productivity growth from period \( t=0 \) to \( t=1 \) in response to the change in the innovation intensity of the economy at time \( t = 0 \), given by

\[
\Gamma_0 = \Theta,
\]

and

\[
\Gamma_{k+1} = [1 - (1 - \phi)\Theta] \Gamma_k \text{ for } k \geq 0.
\] (19)

where \( \Theta \) is the impact elasticity of aggregate productivity defined in equation (16) and \( \log l'_r \text{ for } t, \log \bar{l}_r \text{ for } k \geq 0 \) is given as a function of the transition path for the innovation intensity of the economy as in equation (14).

To help in interpreting the coefficients \( \Gamma_k \) in equation (18), it is useful to consider two example paths for the policy-induced perturbation to the innovation intensity of the economy: one in which the change in the innovation intensity occurs in the initial period 0 only, and one in which the change in the innovation intensity of the economy is permanent.

In the first case, let \( \log l'_r \text{ for } t, \log \bar{l}_r \text{ for } k \geq 0 \) be set such that \( \log l'_r \text{ for } t, \log \bar{l}_r = 1 \), and let this quantity equal 0 at all subsequent dates \( t \geq 1 \). In this case, equation (18) gives that
\( \log Z'_{t+1} - \log Z_{t+1} \approx \Gamma_t \) for \( t \geq 0 \). Given this one-time perturbation to the innovation intensity of the economy, aggregate productivity rises above its initial BGP path by \( \Theta \), and then, if \( \phi < 1 \), gradually returns to that initial BGP path as incomplete intertemporal knowledge spillovers lead the coefficients \( \Gamma_k \) to decay to zero as in equation (19).

In the second case, let \( \log i'_{rt} - \log \bar{i}_r \) be set such that \( \log l'_{r0} - \log \bar{l}_r = 1 \) for all \( t \geq 0 \). In this case, we have \( \log Z'_{t+1} - \log Z_{t+1} \approx \sum_{k=0}^{t-1} \Gamma_k \) for \( t \geq 0 \). Here, aggregate productivity climbs gradually to its new BGP path at a pace determined by the cumulative sums of the coefficients \( \Gamma_k \). Note that in this case, by directly summing the coefficients \( \Gamma_k \), one obtains that this approximation is equal to the exact long-term result in Proposition 1 in the limit.

In the endogenous growth case (\( \phi = 1 \)), the gap in aggregate productivity between the old and new BGP is unbounded. In this case, the new growth rate of aggregate productivity corresponding to a permanent policy-induced change in the innovation intensity of the economy is given to a first-order approximation by

\[
\log Z'_{t+1} - \log Z_t \approx \bar{g}_Z + \Theta \bar{l}_p (\log i'_r - \log \bar{i}_r). \tag{20}
\]

From Proposition 1, we have that in the semi-endogenous growth case (\( \phi < 1 \)), the long run elasticity of aggregate productivity with respect to a permanent change in the innovation intensity of the economy given in equation (15) is independent of the impact elasticity \( \Theta \). This impact elasticity does, however, affect the model’s transition dynamics from the initial BGP to the new BGP as follows.

**Corollary 1.** Consider two specifications of our model (model 1 and model 2) that are calibrated to the same parameter \( \phi < 1 \) governing intertemporal knowledge spillovers and have the same implications for \( \bar{g}_Z \) and the share of output paid to production labor for intermediate goods firms \( (1 + \tau_y)(1 - \alpha)/\mu \) on the initial BGP. Assume that the impact elasticity \( \Theta \) is higher in model 2 than in model 1, i.e. \( \Theta^1 < \Theta^2 \). Then the elasticities \( \{\Gamma_k\} \) defined in Proposition 2 are related in the two models as follows. There exists a cutoff value of \( \bar{K} \) such that \( \Gamma^1_k < \Gamma^2_k \) for \( k < \bar{K} \) and \( \Gamma^1_k > \Gamma^2_k \) for \( k > \bar{K} \). Moreover, for any finite \( K \geq 1 \), \( \sum_{k=0}^{K} \Gamma^1_k < \sum_{k=0}^{K} \Gamma^2_k \). With endogenous growth (\( \phi = 1 \)), \( \Gamma^1_k = \Gamma^2_k \) for all \( K \geq 0 \).

This corollary has the following implications for two example paths for policy induced-perturbations to the innovation intensity of the economy we considered above. In the case of the policy induced perturbation to the innovation intensity of the economy in period \( t = 0 \) only, the resulting change in aggregate productivity is larger in the near term in model 2 than in model 1, but then this impact on aggregate productivity dies out faster in model 2 than in model 1. In contrast, the response of aggregate productivity to a permanent policy-induced change in the innovation intensity of the economy is uniformly
higher at all finite horizons in model 2 than in model 1. In the long-run, as $K \to \infty$, with semi-endogenous growth, the two models deliver the same response of the level of aggregate productivity.

### 3.3 Dynamics of Aggregate Output

We now consider the transition path for aggregate output resulting from an innovation-policy induced perturbation to the innovation intensity of the economy. The following Lemma presents the transition path for aggregate output as a function of the transition paths for aggregate productivity, the allocation of labor, and the equilibrium rental rate on physical capital.

**Lemma 1.** The path of aggregate output corresponding to a policy induced change in the innovation intensity of the economy is given by

$$\log Y'_t - \log \bar{Y}_t = \frac{1}{1-\alpha} (\log Z'_t - \log \bar{Z}_t) + \left( \log l'_{pt} - \log \bar{l}_p \right) - \frac{\alpha}{1-\alpha} \left( \log R'_{kt} - \log \bar{R}_k \right),$$

(21)

where $R_{kt}$ is the rental rate on physical capital and the term $\log l'_{pt} - \log \bar{l}_p$ is given as a function of the innovation intensity of the economy as in equation (14).

A policy-induced increase in the innovation intensity of the economy has two main effects on the path of aggregate output. The first is a direct effect to reduce aggregate output because of the policy induced reallocation of labor from current production of the final consumption good to research. To a first order approximation, this negative effect is captured by the term $\log l'_{pt} - \log \bar{l}_p \approx -\bar{l}_r (\log i'_{rt} - \log \bar{i}_r)$. The second main effect is through the cumulated impact of this policy-induced change in the innovation intensity of the economy on aggregate productivity as captured by the term $\frac{1}{1-\alpha} (\log Z'_t - \log Z_t)$. This effect is equal to zero on impact at $t = 0$ and cumulates over time converging to the limit as specified in proposition 1 with dynamics as specified in proposition 2. The final term in equation (21) reflects changes in the ratio of physical capital to output along the transition from the initial BGP to the final BGP. This term is equal to zero on both the initial and the new BGP. On impact at $t = 0$, aggregate productivity and the stock of physical capital are fixed, so $\left( \log R'_{k0} - \log \bar{R}_k \right) = \left( \log Y'_0 - \log \bar{Y}_0 \right)$ and $\log Y'_0 - \log \bar{Y}_0 = (1-\alpha) \left( \log l'_{p0} - \log \bar{l}_p \right) = - (1-\alpha) \bar{l}_r (\log i'_{r0} - \log \bar{i}_r)$. 
3.4 Welfare

We summarize the welfare gains or losses associated with a new allocation that deviates from an initial BGP by the consumption equivalent change in welfare, defined as the scalar $\zeta$ multiplying the baseline BGP path for consumption required to implement the same change in welfare as is achieved under the new allocation. Under the assumption that the initial baseline BGP allocation of physical capital is not distorted (in the Appendix we introduce a production subsidy that can undo the inefficiencies in physical capital accumulation arising from markups and a corporate profits tax), the following Lemma provides an expression for the consumption equivalent change in welfare corresponding to an innovation-policy induced perturbation of the initial BGP allocation.

**Lemma 2.** If the Euler equation for physical capital is undistorted on the initial BGP so that the rental rate on physical capital is equal to the marginal product of physical capital, then, up to a first order approximation, the consumption equivalent change in welfare corresponding to the macroeconomic dynamics from an innovation-policy induced perturbation of the initial BGP allocation is given by

$$\log \xi \approx (1 - \tilde{\beta}) \sum_{t=0}^{\infty} \tilde{\beta}^t \frac{\bar{Y}}{C} \left[ (\log Z'_t - \log \bar{Z}_t) + (1 - \alpha) \left( \log l'_p t - \log \bar{l}_p \right) \right], \quad (22)$$

where $\tilde{\beta} = \beta \exp (\eta \bar{g}_L + (1 - \eta) \bar{g}_Y)$ is the ratio of the gross growth rate of output to the gross interest rate on the initial BGP.

We see in expression (22) that an increase in the innovation intensity of the economy has two effects on welfare. It will initially decrease the resources available for consumption and physical investment through the reallocation of labor from current production to research, and then increase those resources as aggregate productivity rises in response to firms’ past increased investments in innovation, raising welfare. In this way, our model’s implications for the welfare change corresponding to a change in the innovation intensity of the economy are tightly linked to its implications for the macroeconomic dynamics induced by that change in policies.

Consider now the elasticity of the consumption equivalent change in welfare $\zeta$ with respect to a policy-induced one time change in the innovation intensity of the economy. That is, assume that $\log i'_r 0 - \log i_r = 1$ and let this quantity equal 0 at all subsequent dates $t \geq 1$. As discussed above, in this case, equations (14) and (18) imply that $\log Z'_{t+1} - \log Z_{t+1} \approx \bar{I}_p \Gamma_t$ for $t \geq 0$ and $\log l'_p t - \log \bar{l}_p \approx -\bar{I}_r$ for $t = 0$. From equation (19), we then
have that the elasticity of the consumption equivalent change in welfare is given by

\[
\log \xi \approx (1 - \tilde{\beta}) \left[ \frac{\tilde{\beta} \Theta}{1 - \tilde{\beta} [1 - (1 - \phi) \Theta]} - (1 - \alpha) \frac{I_r}{I_p} \right] \frac{Y}{C_l} I_p, \quad (23)
\]

The elasticity of the consumption equivalent change in welfare that results from a permanent increase in the innovation intensity of the economy is equal to that in equation (23) divided by \(1 - \tilde{\beta}\).

We define the **socially optimal allocation** as the solution to the following problem: choose current production plans of all intermediate goods firms, together with the investments in innovation by those firms and all macroeconomic aggregates to maximize the utility of the representative agent subject to constraints (1) through (11). If the economy starts on the socially optimal allocation, then up to a first order, the change in welfare corresponding to any change in the innovation intensity of the economy should be zero. Hence, on the BGP of the socially optimal allocation, the innovation intensity of the economy should be such that this perturbation has no first order impact on welfare (that is, \(\log \xi = 0\)). That is, the term in the square bracket in equation (23) should be equal to zero. This reasoning leads to the following proposition

**Proposition 3.** On the BGP of the socially optimal allocation, the innovation intensity of the economy is given by

\[
i_r^* = \frac{\tilde{\beta} \Theta}{1 - \tilde{\beta} [1 - (1 - \phi) \Theta]}. \quad (24)
\]

### 3.5 Fiscal Implications

We now consider the fiscal cost of innovation policies required to induce firms to permanently raise the innovation intensity of the economy from \(\bar{i}_r\) to \(\bar{i}_r'\). We characterize the fiscal cost in terms of the change in fiscal expenditures on innovation subsidies relative to aggregate output from the initial BGP to the new BGP to which the economy converges in the next proposition. Note that we have assumed that the policymaker has access to lump sum taxes to finance expenditures on innovation subsidies.

**Proposition 4.** Consider our model on a BGP with semi-endogenous growth and positive firm-entry. Suppose that innovation subsidies change permanently from \(\tau_e\) to \(\tau_e'\). Then, across the initial and new BGPs the innovation intensity of the economy changes from \(\bar{i}_r\) to \(\bar{i}_r'\), and fiscal
expenditures relative to aggregate output change from $E / \bar{Y}$ to $E' / \bar{Y}'$, with these changes given by

$$\log i_r' - \log i_r = \log(1 - \tau_e) - \log(1 - \tau_e')$$

and

$$\frac{\bar{E}'}{\bar{Y}'} - \frac{\bar{E}}{\bar{Y}} = i_r' - i_r.$$

This result implies that in the long-run, changes in innovation subsidies result in a change in the innovation intensity of the economy determined only by the change in the innovation subsidy rate independent of the other parameters of the model. Equivalently, the change in the innovation intensity of the economy in the long-run is equal to the change in fiscal expenditures on these subsidies relative to aggregate output. At short and medium horizons, however, this policy will result in a change in the path of the innovation intensity of the economy from $i_r$ on the initial BGP to $\{i_{rt}^\prime\}_{t=0}^\infty$. The innovation intensity that may vary over time in response to a permanent change in innovation policies because the consumption interest rate and the rate of change in the price of the research good are not constant on the transition path from one BGP to another.

### 3.6 Quantitative Implications for the Impact Elasticity $\Theta$

In our simple model with innovative investment only by entering firms, the impact elasticity $\Theta$ is given from equation (11) by

$$\Theta = \frac{1}{\rho - 1} \frac{\exp(\bar{g}_Z)^{\rho - 1} - \exp(G(0))^{\rho - 1}}{\exp(\bar{g}_Z)^{\rho - 1}},$$

(25)

where $\rho$ is the elasticity of substitution between intermediate goods in the production of the final consumption good $Y_t$, $\bar{g}_Z$ denotes the growth rate of aggregate productivity on the initial BGP to which the model is calibrated, and $G(0)$ denotes the rate of social depreciation of innovative investments.

It is straightforward to show that if $\rho > 1$ and $\bar{g}_Z > 0$, then $\Theta$ is decreasing in $\rho$ and has an upper bound of

$$\Theta \leq \bar{g}_Z - G(0).$$

(26)

This upper bound is achieved when $\rho = 1$.

The bound on the impact elasticity $\Theta$ in equation (26) is not simply a feature of our specific model. Instead, it follows simply from the concavity of the function $G$ defined in equation (11). Specifically, for any concave function $G(Y_r)$, we have $\Theta \equiv G'(Y_r)Y_r \leq$
Once our model is calibrated to a given initial BGP, we have $\bar{g}_Z = G(\bar{Y}_r)$. Equation (26) immediately follows. Intuitively, since $G$ is a concave function, the marginal product of innovative investment on productivity growth is bounded above by its average product.

In our simple model with innovative investment only be entering firms, the term $\bar{g}_Z - G(0)$ can be interpreted as the contribution of innovative investment by entering firms to aggregate productivity growth on the initial BGP.

One implication of expression (26) is that, when evaluating the quantitative implications of specific models for the dynamics of aggregate productivity following a given policy-induced change in the innovation intensity of the economy, we are able to derive an upper bound on the model implied impact elasticity $\Theta$ based on the difference between the initial growth rate of aggregate productivity $\bar{g}_Z$ to which the model is calibrated and the social rate of depreciation $G(0)$ that is typically set implicitly by assumption in the specification of the model. For example, many neo-Schumpeterian models directly assume that if there is no innovative investment, then the level of aggregate productivity remains constant, that is, $G(0) = 0$. With this assumption, the bound on the impact elasticity then simply the BGP growth rate of productivity $\bar{g}_Z$. This bound is quite restrictive quantitatively if the baseline growth rate of productivity $\bar{g}_Z$ to which the model is calibrated on the initial BGP is low. Note that this bound applies regardless of the model’s quantitative implications for micro data on firm dynamics or any other aspect of the data. In contrast, in models in which the social depreciation $G(0)$ is strictly negative, such as expanding varieties models with exogenous exit of products (i.e. in our model, $\delta_e < 1$ and $\delta_0 > 0$) the impact elasticity $\Theta$ is not so tightly restricted quantitatively by this bound.

4 Introducing innovation by incumbent firms

We now introduce innovation by incumbent firms into our model. In the next section we derive conditions under which our analytical results from section 3 hold in this extended model. We specify two technologies available for incumbent firms for innovative investment. One of these allows incumbent firms to acquire products that are new to the firm. The other allows incumbent firms to improve their own existing products. We discuss the models that are nested by our framework after we introduce the technologies that incumbent firms use to invest in innovation.
4.1 Investments in new products by incumbent firms

A firm that owns the frontier technology for producing a particular intermediate good also possesses the capacity to acquire the frontier technology on additional goods through innovative investment. Specifically, if an incumbent firm at $t$ has the frontier technology to produce an intermediate good with index $z$, it also has the opportunity to invest $x_{mt}(z)$ units of the research good to acquire an additional product (new to the firm) at $t + 1$ with probability $h \left( \frac{x_{mt}(z)}{s_t(z)} \right)$, where $s_t(z)$ is defined in (5). Here, $h(\cdot)$ is a strictly increasing and concave function with $h(0) = 0$ and $h(x) < 1$ for all $x$. This technology is specified so that a firm must invest $x_{mt}(z)$ in proportion to the size $s_t(z)$ of its current product with index $z$ at time $t$ to attain any given probability of acquiring a new product at $t + 1$.

Consider now the productivity index $z'$ for a newly acquired product that an incumbent firm obtains at $t + 1$ arising from innovative investment associated with a product with index $z$ at $t$. As is the case with entry, acquisition of new products by incumbent firms may arise from business stealing from other incumbent firms or from the creation of products that are new to society.

With probability $\delta_m$ the product acquired by the incumbent firm at $t + 1$ is stolen from another incumbent firm and has productivity index $z'$ at $t + 1$ drawn at random from a distribution such that the expected value of the term $\exp((\rho - 1)z')$ is equal to $\mathbb{E}\exp((\rho - 1)z)$, with $\eta_{ms} > 1$. We assume that the product it displaces had productivity $z$ at $t$.

With complementary probability $1 - \delta_m$ the newly acquired product is new to society. We assume that the productivity index $z'$ in this case is drawn from a distribution such that the expected value of the term $\exp((\rho - 1)z')$ is equal to $\mathbb{E}\exp((\rho - 1)z') = \eta_{mn}\exp((\rho - 1)z)$, with $\eta_{mn} > 0$. We define $\eta_m = \delta_m\eta_{ms} + (1 - \delta_m)\eta_{mn}$.

We define the aggregate quantity of this type of innovative investment by incumbent firms as

$$x_{mt} \equiv \sum_z x_{mt}(z) M_t(z).$$

\cite{Klette and Kortum 2004} considers a variation of this investment technology for incumbent firms to acquire new products. In that alternative formulation, the probability of acquiring a new product is $h(\frac{x_{mt}(z)}{s_t(z)})$ (as opposed to $h(\frac{x_{mt}(z)}{s_t(z)})$) and the expected productivity of a new product satisfies $\mathbb{E}\exp((\rho - 1)z') = \eta_m Z_t^{\rho - 1}/M_t$ (as opposed to $\eta_m\exp((\rho - 1)z)$. Our analytic results given below are unchanged under this alternative formulation. Our measurement procedure, however, needs to be slightly amended because firm value is not proportional to size. Assuming a positive correlation between firm size and the average size of a firm’s products, this alternative specification can generate a negative correlation between firm size and innovation intensity and between firm size and expected growth rate (see e.g. \cite{Akcigit and Kerr 2017}). Details are available upon request.
4.2 Investment in continuing products by incumbent firms

Incumbent firms have research capacity associated with each product that they produce at $t$ that allows them to invest to improve the index $z$ of that product if they retain it at $t + 1$. We assume that if an incumbent firm with a product with productivity $z$ at $t$ spends $x_{ct}(z)$ of the research good on improving that product, it draws a new productivity index $z'$, conditional on not losing that product to exogenous exit or business stealing, from a distribution such that the expectation of $\exp((\rho - 1)z')$ is

$$\mathbb{E}\exp((\rho - 1)z') = \zeta \left( \frac{x_{ct}(z)}{s_t(z)} \right) \exp((\rho - 1)z).$$

We assume that $\zeta(\cdot)$ is a strictly increasing and concave function, with $\zeta(x) > 0$ for all $x \geq 0$. Note that the investment $x_{ct}(z)$ required to achieve a given expected growth of $\exp((\rho - 1)z)$ scales with the size $s_t(z)$ of the product being invested in at $t$.

We assume that $\eta_{es} > \zeta(x)$ and $\eta_{ms} > \zeta(x)$ for all $x$. These inequalities correspond to the requirement that a product that is stolen from incumbent firms is, in expectation, produced with a higher $z'$ at $t + 1$ in its new firm than it would have had as a continuing product in the firm that previously produced it. Equivalently, stolen products have larger average size than continuing products in incumbent firms. We also assume that $(1 - \delta_0 - \delta_m h(x_m) - \delta_e x_e) > 0$. These assumptions are justified if the time period in the model is short enough.\(^{14}\)

We define the aggregate quantity of this type of innovative investment by incumbent firms as

$$x_{ct} \equiv \sum_z x_{ct}(z) M_t(z).$$

With these investment technologies for incumbent firms, the resource constraint for the research good is given by

$$x_{ct} + x_{mt} + x_{et} = Y_{rt}. \quad (27)$$

We define a BGP in this extended model in the same manner as we did in section 2.6, except here we add the condition that each category of aggregate real innovative investment also be constant over time, i.e. $x_{ct} = \bar{x}_c$, $x_{mt} = \bar{x}_m$, and $x_{et} = \bar{x}_e$.

\(^{14}\)This is because $\zeta(x)$ denotes the expected improvement per unit of time in $\exp((\rho - 1)z)$ for an incumbent firm and hence shrinks to 1 as the length of the time period shrinks to zero. Likewise, $\delta_0$, $\delta_e$, $\delta_m$, $h(x_m)$ and $x_e$ are all rates per unit of time that shrink to zero as the length of the time period shrinks to zero. In contrast, $\eta_{es}$ and $\eta_{ms}$ correspond to the realized improvement in $\exp((\rho - 1)z)$ for products that are stolen. These parameters are assumed to be independent of the time period.
4.3 Nested models

Our model nest five commonly used models in the literature: three types of Expanding Varieties models and two types of Neo-Schumpeterian models.

If $\delta_e = \delta_m = 0$, then there is no business stealing and hence all new products acquired by incumbent and entering firms are new products for society, expanding the measure of products $M_t$. This is the assumption typically made in an Expanding Varieties model. Luttmer (2007b) is an example of an expanding varieties model in which there is only innovative investment in entry. (Note that we do not consider the endogenous exit of products due to fixed operating costs featured in that paper). Atkeson and Burstein (2010) is an example of an expanding varieties model in which there is innovative investment in entry and by incumbent firms in continuing products. Luttmer (2011) is an example of an expanding varieties model in which there is innovative investment in entry and in the acquisition of new products by incumbent firms.

Neo-Schumpeterian models based on the Quality-Ladders framework typically assume $\delta_e = \delta_m = 1$ and $\delta_0 = 0$. The simplest versions of these models do not accommodate growth in the measure of varieties $M_t$. Grossman and Helpman (1991a) and Aghion and Howitt (1992) are examples of Neo-Schumpeterian models in which there is only innovative investment in entry. Klette and Kortum (2004) is an example of a Neo-Schumpeterian model in which there is innovative investment in entry and by incumbent firms in acquiring new products (new to the firm, not to society). Acemoglu and Cao (2015) is an example of a Neo-Schumpeterian model in which there is innovative investment in entry and by incumbent firms in improving their own products.

4.4 Innovative Investment and Productivity Growth

We consider innovation policies that can be applied to each of the three categories of innovative investment ($x_{ct}$, $x_{mt}$ and $x_{et}$). Throughout we assume that subsidy rates are category-specific but not specific to individual firms or products. We refer to these category-specific subsidies as $\tau_{ct}$, $\tau_{mt}$ and $\tau_{et}$. We say these innovation subsidies are uniform if $\tau_{ct} = \tau_{mt} = \tau_{et}$.

With the category-specific policies and innovative investment technologies for incumbent firms that we have specified above, in equilibrium, the innovation expenditures associated with each product produced by an incumbent firm are directly proportional to the size of these products. Moreover, when firms’ innovative investments are directly proportional to the size of the products that they produce, the resulting dynamics for the size of existing products are consistent with a strong form of Gibrat’s Law — the growth
and death rates of products are independent of the size of a product. Given these two features of the equilibrium of the model, we characterize the growth rate of aggregate productivity as a simple function of current aggregate real innovative investment in each of the categories of investment by incumbents and entrants as follows.

**Lemma 3.** In an equilibrium with innovation policies applied to each category of innovative investment as described above, the dynamics of aggregate productivity as a function of innovative investment by firms are summarized by

\[
g_{zt} = \log(Z_{t+1}) - \log(Z_t) = G(x_{ct}, x_{mt}, x_{et}),
\]

where \( G \) is given by

\[
G(x_{ct}, x_{mt}, x_{et}) = \frac{1}{\rho - 1} \log \left( (1 - \delta_0 - \delta_m h(x_{mt}) - \delta_e x_{et}) \zeta(x_{ct}) + \eta_m h(x_{mt}) + \eta_e x_{et} \right). 
\]  

We define the social depreciation rate of innovation expenditures in this extended model as \( G^0 \equiv G(0, 0, 0) \).\(^{15}\)

As shown in Lemma 3, the growth rate of aggregate productivity from period \( t \) to period \( t + 1 \) is a simple function of the aggregate quantities of the three categories of innovative investment undertaken by firms: \( x_{ct}, x_{mt}, x_{et} \). In particular, our assumptions imply that we do not have to keep track of the details of the distribution \( M_t \) of indices \( z \) across intermediate goods or of other attributes of incumbent firms to calculate the equilibrium relationship between incumbent firms’ innovative investments and the growth rate of aggregate productivity. However, in order to make positive or normative predictions regarding a policy-induced change in aggregate real innovative investment \( Y_{rt} \), we must consider how this policy change impacts the allocation of innovative investment across each of the three categories, \( x_{ct}, x_{mt}, \) and \( x_{et} \).

We generalize our definition of the impact elasticity \( \Theta \) as follows. For \( i = c, m, e \), we let

\[
\Theta_i = \frac{\partial}{\partial x_i} G(\bar{x}_c, \bar{x}_m, \bar{x}_e) \bar{Y}_r
\]

de note the impact elasticity of a change in aggregate innovation expenditure devoted entirely to changing investment category \( x_i \), with this elasticity evaluated at the initial BGP allocation of investment. Since the sum of investments across categories must equal total investment, we can write the impact elasticity of any particular policy induced perturba-

\(^{15}\)In our model, \( G^0 = \frac{1}{\rho - 1} \log \left( (1 - \delta_0) \zeta \right) (0) \), where \( (1 - \delta_0) \zeta \) (0) corresponds to the expected growth rate of \( \exp ((\rho - 1) z) \) of incumbent products if no firms invest in innovation. \( G^0 \) can be positive or negative. We speculate that social depreciation of innovation expenditures may be derived from the fact that productive knowledge in firms is embodied in individuals who are familiar both with the knowledge gained through innovation and the procedures for training new workers in that knowledge, and the work force within firms is constantly turning over and workers themselves have a life cycle.
tion of innovative investment as

\[ \Theta = \Theta_c \frac{dx_c}{dY_r} + \Theta_m \frac{dx_m}{dY_r} + \Theta_e \frac{dx_e}{dY_r} \]  (30)

where the terms \( dx_i/dY_r \) indicate how, at the margin, any particular change in aggregate innovative investment is allocated across categories subject to the constraint imposed by the resource constraint (27) that

\[ \frac{dx_c}{dY_r} + \frac{dx_m}{dY_r} + \frac{dx_e}{dY_r} = 1. \]

The parameter assumptions we have made above ensure that the terms \( \Theta_c, \Theta_m, \Theta_e > 0 \) on the initial BGP. With additional restrictions on policies, we can also rank these terms on the initial BGP. We present these results in the following lemma.

**Lemma 4.** Our assumptions that \( \eta_{en}, \eta_{mn} > 0 \), and that \( \eta_{es} > \zeta(x_c), \eta_{ms} > \zeta(x_c), \text{ and } 1 - \bar{\delta}_c = 1 - \delta_0 - \delta_m h(\bar{x}_m) - \delta_e \bar{x}_e > 0 \) on the initial BGP imply that \( \Theta_c, \Theta_m, \Theta_e > 0 \). If the policies on the initial BGP satisfy \( \tau_e \geq \tau_c \) on the initial BGP, then \( \Theta_c \geq \Theta_e \). Likewise, if \( \tau_m \geq \tau_c \) then \( \Theta_c \geq \Theta_m \).

We maintain the assumptions on policies on the initial BGP required to ensure that \( \Theta_c \geq \Theta_e \) throughout the remainder of this paper.

5 Extending Analytical Results

In this section we establish conditions under which we can apply our analytical results from Section 3 in this model. In subsection 5.1 we show that these results can be applied if the allocation of real innovative investment on the initial BGP is conditionally efficient as defined below. In subsections 5.2 and 5.3 we present extensions of our our results from Section 3 that follow when the allocation of innovative investment on the initial BGP is not conditionally efficient.

5.1 Conditional Efficiency on the Initial BGP

In this subsection, we show that the positive and normative results from section 3 extend to this model with innovative investment by incumbent firms when the equilibrium allocation of innovative investment on the initial BGP is conditionally efficient. Specifically, we say that the vector of investments \( x_{ct}, x_{mt}, x_{et} \) is *conditionally efficient* if it is interior, so
that \( x_{ct}, x_{mt}, x_{et} > 0 \), and it solves the problem of minimizing

\[
\bar{Y}_r^* = \min_{x_c, x_m, x_e} x_c + x_m + x_e
\]

subject to the constraint that \( G(x_c, x_m, x_e) = \bar{g}Z \).

Note that if the initial BGP allocation is conditionally efficient, then equation (30) implies that \( \Theta = \Theta_c = \Theta_m = \Theta_e \). Hence the model-implied impact elasticity \( \Theta \) of aggregate productivity growth with respect to a policy induced change in aggregate innovative investment in equation (30) is independent of the details of how a change in policy results in a reallocation of innovative investment across categories, as captured in the terms \( dx_c/dY_r \), \( dx_m/dY_r \), and \( dx_e/dY_r \) in equation (30).

We next present a result on conditions under which the equilibrium allocation of innovative investment on the initial BGP is conditionally efficient.

**Lemma 5.** Assume that under uniform policies, there exists an equilibrium allocation of innovative investment on an initial BGP that is interior. Then this equilibrium allocation of innovative investment is conditionally efficient if either (i) there is no business stealing \( (\delta_m = \delta_e = 0) \) or (ii) there is no marginal return to investment by incumbents in improving their own products \( (i.e. \zeta(x) = \bar{\zeta} \text{ for all } x \text{ and } x_{ct} = \bar{x}_c \text{ is simply an exogenous parameter}) \), and if the extent of business stealing and the expected size of new products acquired by entrants and incumbent firms are equal \( (i.e. \delta_m = \delta_e \text{ and } \eta_m = \eta_e) \). Alternatively, for any parameter values, given a conditionally efficient allocation of innovative investment, we can choose initial policies such that this allocation is also the equilibrium allocation of innovative investment on the BGP corresponding to those policies.

We then have the following extensions of our analytical results if the allocation on the initial BGP is conditionally efficient.

**Proposition 5.** If the allocation of innovative investment on an initial BGP is conditionally efficient, then the dynamics of aggregate productivity and output with respect to a policy-induced change in the innovation intensity of the economy are given as in Proposition 2 and Lemma 1. The formula in Proposition 1 for the change in aggregate productivity across BGPs as a function of the policy induced reallocation of labor to research across BGPs, holds to a first order approximation and is an upper bound on the actual change in aggregate productivity across BGPs. The upper bound on the impact elasticity \( \Theta = \Theta_e \) given in equation (26) applies. The welfare implications of policy-induced changes in the innovation intensity of the economy is given as in Lemma 2. If the innovation policies on the initial and new BGPs are uniform, then the fiscal cost of the policies required to induce a given change in the innovation intensity of the economy is given as in Proposition 4.
We next provide results regarding the dynamics of aggregate productivity following a change in innovation policies in the more general case in which the allocation of innovative investment on the initial BGP is not conditionally efficient.

5.2 Productivity Dynamics without conditional efficiency

As discussed above, in the event that the initial allocation of innovative investment on the initial BGP is not conditionally efficient, then the positive implications of our model for the impact elasticity $\Theta$ depend on the specifics of the reallocation of aggregate innovative investment across categories of investment as specified in the terms $dx_c/dY_r$, $dx_m/dY_r$, and $dx_e/dY_r$ in equation (30) in response to any given change in innovation policies. In addition, the model’s implied impact elasticity may vary over time if the perturbation to innovation policies varies over time.

To make progress in deriving analytical results, we restrict attention to new innovation policies $\tau'_{ct}$, $\tau'_{mt}$, $\tau'_{et}$ such that the relative subsidies of innovative investment by incumbent and entering firms are constant over time in the sense that

$$\frac{1 - \tau'_{ct}}{1 - \tau'_e} = \frac{1 - \tau'_c}{1 - \tau'_e} \quad \text{and} \quad \frac{1 - \tau'_{mt}}{1 - \tau'_e} = \frac{1 - \tau'_m}{1 - \tau'_e} \quad \text{(32)}$$

for all $t \geq 0$. While we do allow the level of subsidies as indexed by $\tau'_e$ to vary over time, we do require that it converge to a constant $\tau'_e$ corresponding to a new BGP. With these assumptions, we then have the following Proposition extending Propositions 1 and 2.

**Proposition 6.** Consider the equilibrium transition of an economy from an initial BGP to a new BGP given new innovation policies that satisfy condition (32). If the allocation of innovative investment on the new BGP and on the transition to that BGP is interior, and if the extent of business stealing by entrants as indexed by $\delta_e$ is small enough relative to the curvature of the function $\zeta$, then the dynamics of aggregate productivity are given, to a first order approximation by

$$\log Z'_{t+1} - \log \bar{Z}_{t+1} \approx \sum_{k=0}^{t} \Gamma'_k \left[ \log l'_{r(t-k)} - \log \bar{I}_r - (\log \bar{Y}'_r - \log \bar{Y}_r) \right]$$

where $\Gamma'_0 = \Theta'$ and $\Gamma'_{k+1} = [1 - (1 - \phi)\Theta'] \Gamma'_k$. The impact elasticity $\Theta'$ is given by equation (30) independent of the date $t$, with the terms $\Theta'_i$ defined as in equation (29) evaluated at the new BGP allocation of innovative investment $\bar{x}'_c$, $\bar{x}'_m$, $\bar{x}'_e$, and with $dx_m/dY_r = 0$.

$$\frac{dx'_e}{dY_r} = \left[ 1 + \frac{\delta_e \zeta'(\bar{x}'_e)}{(1 - \delta_0 - \delta_m h(\bar{x}'_m) - \delta_e \bar{x}'_e) \zeta''(\bar{x}'_e)} \right]^{-1}.$$
and
\[ \frac{dx_c}{dY_r} = 1 - \frac{dx_e}{dY_r}. \]

The allocation of labor to research is related to the innovation intensity of the economy as in equation (14). Given this first order approximation to the path of aggregate productivity, equation (21) for the dynamics of GDP and equation (22) characterizing the consumption equivalent measure of welfare apply.

The restriction that \( \delta_e \) be small enough relative to \( \zeta''(\cdot)/\zeta'(\cdot) \) in this proposition is required to ensure that the impact elasticity \( \Theta' > 0 \). The possibility that the impact elasticity \( \Theta' \) might be negative in a model of this kind is discussed in Acemoglu and Cao (2015).

The dynamics of productivity described in Proposition 6 differ from those described in Proposition 2 in two respects. First, the impact elasticity \( \Theta' \) used in Proposition 6 is evaluated at the allocation of real innovative investment on the new BGP rather than on the initial BGP (as is the case with \( \Theta \) above). Second, the term \( \log \bar{Y}'_r - \log \bar{Y}_r \) reflecting the change in the level of aggregate real innovative investment between the initial BGP and the new BGP impacts the dynamics of productivity in the same way as a reallocation of labor from production to research. In this sense, an increase in the efficiency of innovative investment (in lowering the real quantity of investment required to attain BGP productivity growth rate \( \bar{g}_Z \)) has an impact on the dynamics of TFP equivalent to an increase in the allocation of labor to research.

One could use the results in Proposition 6 to assess the aggregate implications of arbitrary changes in innovation policies that satisfy condition (32) if one specifies all of the parameters of our model including the technologies for innovative investment \( h(\cdot) \) and \( \zeta(\cdot) \). To do so, one would specify a particular change in policies, compute the allocation of innovative investment on the new BGP, and then compute the model implied values of the impact elasticity \( \Theta' \) and the efficiency gain (or loss) embodied in the term \( \log \bar{Y}'_r - \log \bar{Y}_r \). In this case, the two statistics \( \Theta \) (on the original BGP) and \( \phi \) are no longer sufficient to approximate the dynamics of productivity.

We conclude our analytical results regarding the dynamics of productivity by characterizing a restricted class of perturbations to innovation policies such that the productivity dynamics in Proposition 6 coincide with those in Proposition 2. For this restricted class of policy changes, the two statistics \( \Theta \) on the original BGP and \( \phi \) are sufficient to conduct our analysis.
5.3 Proportional Policy Changes

Let $\tau_c$, $\tau_m$, and $\tau_e$ denote the innovation subsidies on the initial BGP. Let the new innovation subsidies starting in period $t = 0$ satisfy (32) and the condition that they converge to constants $\tau'_c$, $\tau'_m$, and $\tau'_e$ such that

\[ \frac{1 - \tau'_c}{1 - \tau_c} = \frac{1 - \tau'_m}{1 - \tau_m} = \frac{1 - \tau'_e}{1 - \tau_e}. \]  

(33)

With this restriction that the policies on the new BGP are proportional to those on the initial BGP as in (33), we can show that the allocation of real innovative investment on the new BGP is equal to that on the old BGP. As a result, $\bar{Y}'_r = \bar{Y}_r$ and the impact elasticity $\Theta'$ as defined in Proposition 6 is equal to that computed at the allocation of innovative investment on the initial BGP (and hence denoted by $\Theta$). We prove these results and their further implications in the following proposition.

**Proposition 7.** Consider a change in policies from $\tau_c$, $\tau_m$, $\tau_e$ to $\tau'_c$, $\tau'_m$, $\tau'_e$ that satisfy equations (32) and (33). Assume that the allocation of innovative investment on the initial BGP is interior. Then, the allocation of real innovative investment is the same on the initial and new BGP’s. As a result, the change in aggregate productivity across the initial and new BGP’s is given as in Proposition 1 and the dynamics of aggregate productivity from the initial to the new BGP are given to a first order approximation as in Proposition 2 where the impact elasticity $\Theta$ is computed as in Proposition 6 with derivatives evaluated at the initial BGP allocation of real innovative investment. The dynamics of GDP and the calculation of the welfare impact of the policy change are as in Lemmas 1 and 2. Under the further restriction that the initial (and final) policies are uniform, then the fiscal cost of these policies is related to the policy induced change in the innovation intensity of the economy as in Proposition 4.

As a corollary to this proposition, we next show that we can bound the impact elasticity $\Theta$ corresponding to a proportional policy change by the impact elasticity with respect to entry $\Theta_e$.

**Corollary 2.** Assume that the allocation of innovative investment on the initial BGP is interior and that $\delta_e$ is small enough relative to the curvature of the function $\zeta$. Then the impact elasticity $\Theta$ corresponding to a proportional change in policies satisfying equations (32) and (33) is bounded above by $\Theta_e$.

The restriction that $\delta_e$ be small enough relative to $\zeta''(\cdot)/\zeta'(\cdot)$ in this Corollary is required to ensure that the impact elasticity $\Theta > 0$ and that $\frac{dx_c}{dY_r} < 0$.

We now turn to the question of what data we might use to measure the key parameters of our model.
6 Measurement

In this section, we use our analytical results to measure the aggregate implications of a change in innovation policies for the dynamics of aggregate productivity and output. We focus here on an economy that starts with uniform subsidies for innovative investment and we consider the implications of a proportional change in policies to a new, higher, level of uniform innovation subsidies. We consider one specification of the model in which there is no business stealing, which implies that the allocation of innovative investment on the initial BGP is conditionally efficient. In this case, the impact elasticity is \( \Theta = \Theta_e \). We consider an alternative specification of the model in which the allocation of innovative investment on the initial BGP is not conditionally efficient due to business stealing. In this case, Corollary 2 implies that \( \Theta \leq \Theta_e \). In both cases, then, we measure \( \Theta_e \) and use this measure of the impact elasticity to characterize the aggregate implications of a uniform change in innovation policies.

Given the functional form for \( G \) in equation (28), we can calculate the term \( \Theta_e \) directly as

\[
\Theta_e = \frac{1}{\rho - 1} \left[ \frac{\exp(\bar{g}_Z) - \exp(G(\bar{x}_c, \bar{x}_m, 0))}{\exp(\bar{g}_Z)} \right] \frac{\bar{Y}_r}{\bar{x}_e}. \tag{34}
\]

We provide formulas for \( \Theta_c \) and \( \Theta_m \) in the Appendix.

We can derive a bound on \( \Theta_e \) similar to the one we obtained in equation (26) for the model with innovative investment by entrants only. Specifically, given the definition that \( \Theta_e \equiv \frac{\partial}{\partial x_e} G(\bar{x}_c, \bar{x}_m, \bar{x}_e) \bar{Y}_r \), concavity of the function \( G(\bar{x}_c, \bar{x}_m, x_e) \) in its third argument \( x_e \) implies that \( \frac{\partial}{\partial x_e} G(\bar{x}_c, \bar{x}_m, \bar{x}_e) \leq \frac{(\bar{g}_Z - G(\bar{x}_c, \bar{x}_m, 0))}{\bar{x}_e} \). This argument gives the bound

\[
\Theta_e \leq \frac{(\bar{g}_Z - G(\bar{x}_c, \bar{x}_m, 0))}{\bar{x}_e} \bar{Y}_r, \tag{35}
\]

where this bound is tight as \( \rho \to 1 \). The term \( \bar{g}_Z - G(\bar{x}_c, \bar{x}_m, 0) \) can be interpreted as the contribution of innovation by entering firms to productivity growth on the initial BGP, and \( \bar{x}_e/\bar{Y}_r \) is the fraction of innovative investment undertaken by entering firms. Once one knows the term \( \bar{g}_Z - G(\bar{x}_c, \bar{x}_m, 0) \), it is straightforward to calculate the term in square brackets in equation (34).

We measure \( \Theta_e \) using equation (34). We set the elasticity of substitution between goods \( \rho = 4 \). To measure the contribution of innovation by entering firms to produc-

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\(^{16}\)We use this upper bound on the impact elasticity to avoid having to make additional assumptions regarding the curvature of the technology \( \xi(x_c) \) for innovative investment as required in the statement of Proposition 6 to compute the terms \( dx_e/dY_r \) and \( dx_c/dY_r \).
tivity growth on the initial BGP and the fraction of innovative investment undertaken by entering firms, we make use of data on firm dynamics, firm value, the innovation intensity of the economy, and the interest rate and growth rate of output on the initial BGP as described next. In explaining our measurement procedure, we use the following notation for the data on firm dynamics and firm value.

Let $s_{t+1}$ denote the aggregate size of products produced in entering firms at $t + 1$ measured as the share of revenues (and employment and physical capital $K_{t+1}$) produced by firms that start production at $t + 1$. This measure of size corresponds to the sum of product size $s_{t+1}(z)$ as defined in equation (5) across all products produced at $t + 1$ by firms that newly entered at that date. Let $\bar{s}_e$ denote the size of entering firms on the initial BGP, which we measure using firm dynamics data from the Longitudinal Business Database on the share of total employment in new firms (created within the past year).

Now consider the concept of firm value that we use in our measurement. In our model, the dividends $D_t$ that households receive as owners of all incumbent firms at time $t$ (see the budget constraint in equation 12) are equal to the monopoly profits that incumbent firms earn on their production less post-subsidy expenditures on innovative investment by these incumbent firms. $V_t$ denotes the discounted present value of these dividends from period $t$ on. Let $d_t = D_t / Y_t$ and $v_t = V_t / Y_t$ denote the ratios of these dividends and value to output at time $t$, and let $\bar{d}$ and $\bar{v}$ denote these ratios of dividends and value to output on a BGP. As described in Appendix C, when measuring dividends in the data we allow for a corporate profits tax.

The associated ratio of the value of these dividends to output $\bar{v}$ on the initial BGP is then given by

$$\bar{v} = \bar{d} \left[ 1 - \frac{\exp (\bar{g}_Y)}{1 + \bar{R}} (1 - \bar{s}_e) \right]^{-1}. \quad (36)$$

We use NIPA data for the non-financial corporate sector to measure the expenditure on innovative investment by incumbent firms $P_{rt} (x_{ct} + x_{mt})$ relative to output, and use the condition that entrants earn zero profits to infer the ratio of innovative investment by entrants to output on the initial BGP

$$\frac{P_{rt} \bar{x}_e}{\bar{Y}_t} = \frac{\exp (\bar{g}_Y)}{1 + \bar{R}} \frac{\bar{v}}{(1 - \bar{v})^{\bar{s}_e}}. \quad (37)$$

The innovative intensity of the economy $\bar{i}_e$ is given by the sum of innovative investments by incumbent firms and our imputed measure of innovative investment by entering firms. These formulas allow us to measure the fraction of innovative investment undertaken by entering firms, $\bar{x}_e / \bar{Y}_r$.
We draw on external estimates of the interest rate $\bar{R}$ and $\bar{\tau}_e = \bar{\tau}_c = \bar{\tau}_m$ on the initial BGP. As described in Appendix C, we use NIPA data for the non-financial corporate sector to measure the growth rate of output $\bar{g}_Y$, the share of physical capital in the production function $\alpha$, the markup $\mu$, dividends relative to output $\bar{d}$ on the initial BGP, and the innovative investment of incumbent firms $\bar{P}_t (\bar{x}_c + \bar{x}_m)$ relative to aggregate output. Throughout our calculations, we consider a period to be one year.

We consider one specification of our model with no business stealing, that is $\delta_m = \delta_e = 0$. Under the assumption that there is no business stealing, the term in square brackets in equation (34) is equal to $\bar{s}_e$, so that

$$\Theta = \Theta_e = \frac{1}{\rho - 1} \bar{s}_e \bar{Y}_r. \tag{38}$$

With $\rho = 4$, $\bar{s}_e = 0.027$, and $\bar{x}_c / \bar{Y}_r = 0.34$, our estimate of the impact elasticity in this case is $\Theta = 0.026$. This impact elasticity is substantially higher than the bound in equation (26) of $\bar{g}_Z$ that would apply if there were no social depreciation of innovation expenditures ($G^0 = 0$). Thus, under the assumption of no business stealing, our measurement indicates that there is social depreciation of innovation expenditures.

We consider an alternative specification of our model that includes business stealing, that is $\delta_m, \delta_e > 0$. In this case, the initial equilibrium is not conditionally efficient. For these specifications of our model, we set $\Theta$ equal to its upper bound, $\Theta_e$ (as shown in Corollary 2). To measure $\Theta_e$ in this case, we can no longer set the term in square brackets in (34) equal to $\bar{s}_e$. Instead, we draw on external estimates of the contribution of entrants to productivity growth on the initial BGP to measure this term. Specifically, we choose $G(\bar{x}_c, \bar{x}_m, 0)$ so that $(\bar{g}_Z - G(\bar{x}_c, \bar{x}_m, 0)) / \bar{g}_Z = 0.257$, which corresponds to estimates of the portion of annual trend productivity growth due to entry in Akcigit and Kerr (2017).\(^{17}\) (With this measure of the contribution of innovation by entrants to growth, the term in square brackets in equation (34) is equal to 0.011, which is substantially less than $\bar{s}_e$.) Hence, our measure of the impact elasticity is $\Theta_e = 0.01$.

In our analysis of the aggregate implications of changes in innovation policies, we use external estimates of the degree of intertemporal knowledge spillovers $\phi$. Specifically, we consider two alternative values. We consider a high degree of intertemporal knowledge spillovers, $\phi = 0.96$, which is close to the value assumed in the literature with fully endogenous growth. As an alternative, we consider a low degree of intertemporal knowledge spillovers, $\phi = -1.6$, taken from estimates of this parameter in Fernald and Jones

To summarize, in the next section we discuss the following four specifications of our model: one with no business stealing ($\Theta = 0.026$) and low intertemporal knowledge spillovers ($\phi = -1.6$), one with no business stealing and high intertemporal knowledge spillovers ($\phi = 0.96$), and two more with business stealing ($\Theta = 0.01$) and low and high intertemporal knowledge spillovers, respectively. The full set of parameters that we use in our calculations is given in Table 2 in Appendix C.

7 Results

In each of the four calibrations of our model, we consider the dynamics of aggregate productivity and output that follow from a proportional policy change starting at $t = 0$ that induces a permanent, constant increase in the allocation of labor to research (that is, $\log l_r' - \log \bar{l}_r$ is positive and constant for $t \geq 0$). This reallocation of labor corresponds to a permanent increase in the innovation intensity of the economy given by equation 14. In the long-run, the fiscal cost and the rates of the innovation subsidies required to implement this increase in the innovation intensity of the economy are given as in Proposition 4. We compute the path of innovation subsidies required to implement this reallocation of labor in the transition numerically.\footnote{In Appendix C we compare our results using our log-linear approximation with those from the fully non-linear solution, and they are very similar.}

In the first three rows of Table 1, we report the elasticity of aggregate productivity relative to trend ($\log Z_i' - \log \bar{Z}_i$) with respect to this permanent change in the allocation of labor at horizons of $t = 1$ year, $t = 20$ years, and $t = \infty$. From Proposition 2, the elasticity of aggregate productivity at one year is given by the impact elasticity $\Theta$ and the elasticity of aggregate productivity at 20 years is given by $\sum_{k=0}^{19} \Gamma_k$. From Proposition 1, the long run elasticity of aggregate productivity is given by $1/(1 - \phi)$.

In rows 4-6 of Table 1, we report the elasticity of aggregate output relative to trend ($\log Y_i' - \log \bar{Y}_i$) with respect to this permanent change in the allocation of labor on impact (at $t = 0$) and at horizons of $t = 20$ years and $t = \infty$. From Lemma 1, the elasticity of output on impact is given by $- (1 - \alpha) \bar{l}_r / \bar{l}_p$. The elasticity of output at $t = 20$ is given by $\sum_{k=0}^{19} \Gamma_k / (1 - \alpha) - \bar{l}_r / \bar{l}_p$ plus an adjustment for changes in the rental rate along the transition that we compute numerically. The elasticity of output in the long run is given by $\frac{1}{(1 - \phi)(1 - \alpha)} - \bar{l}_r / \bar{l}_p$.

In row 7 of Table 1, we report the elasticity of the consumption equivalent change in welfare calculated equation (23) (we assume that there is a production subsidy that
undoes the markup distortion on physical capital investment) and in row 8 we report the innovation intensity of the economy on the socially optimal BGP, as given in Proposition 3.

**Interpreting elasticities** To help interpret these elasticities in Table 1, we consider a change in innovation policies that results in a permanent change in the allocation of labor of \(\log l'_{rt} - \log \bar{l}_r = 0.1\). The implied responses of aggregate productivity, output, and welfare are equal to the elasticities given in rows 1-7 of Table 1 multiplied by 0.1. This change in the allocation of labor corresponds, in our calibration, to a permanent change in the innovation intensity of the economy from \(\bar{i}_r = 0.089\) to \(\bar{i}'_r = 0.10\). The corresponding annual fiscal cost of these policies in the long run is then equal to 1.1% of output.

Consider first the implied long run elasticities of aggregate productivity and output in response to this policy change. In the two specifications of the model with low intertemporal knowledge spillovers (low \(\phi\)) the long run responses of aggregate productivity and output are relatively modest, equal to 3.8% for each. In contrast, in the two specifications of the model with high intertemporal knowledge spillovers, the long-run responses of aggregate productivity and output (in logs) are 65 and 91 times larger, respectively. It is clear that the model’s implications for long run productivity and output are very sensitive to the calibration of intertemporal knowledge spillovers, \(\phi\). In contrast, these implications are independent of the impact elasticity \(\Theta\).

As discussed in corollary 1, the impact elasticity \(\Theta\) interacts with the intertemporal knowledge spillovers \(\phi\) to shape the dynamics of aggregate productivity and output from the initial BGP to the new BGP. In row 4 of Table 1, we see that the initial \((t = 0)\) response of output to this policy-induced reallocation of labor is to fall by 1.1% in all four specifications of our model. The response of aggregate productivity in year 1 (in row 1) is 0.26% (26 basis points) with no business stealing and 0.1% with business stealing. This relatively small response of aggregate productivity implies that aggregate output is below trend for the first 6 years of the transition in the case with no business stealing and for the first 15 years of the transition in the case with business stealing.

By year \(t = 20\), aggregate output is above trend in all cases (row 5), but the response is not that large. With no business stealing, output is 2.0% (4.2%) above trend with low (high) intertemporal knowledge spillovers. With business stealing, by year \(t = 20\), output is only 0.3-0.7% above trend, depending on the extent of intertemporal knowledge spillovers.

We draw two conclusions from these results. First, we see that the medium term elasticity of output is not that sensitive to the assumed intertemporal knowledge spillovers
in comparison to what is found for the long run elasticities. Second, these small model-implied responses of aggregate output after 20 years suggest that it might be difficult to see the impact on aggregates of a change in innovation policies of this magnitude over a horizon of two decades in the presence of normal business cycle shocks. That is, in a world in which the standard deviation of output per worker around trend is 2 to 3%, policy-induced movements in output of the magnitudes considered here are relatively small. In this respect, our findings rationalize empirical studies finding a weak link between R&D and productivity growth using time series data, see e.g. CBO 2005.

The modest responses of aggregate productivity and output over a 20 year horizon implied by the elasticities in rows 2 and 5 of Table 1 stand in contrast to our model’s normative implications for innovation policies. In row 7 of Table, we see that the consumption equivalent variation corresponding to this policy change ranges from 1.7% to 20% of aggregate consumption, all from a policy change with annual fiscal costs in the long run of only 1.1% of GDP. Likewise, in row 8 of Table 1, we see that our model’s implications for the innovation intensity of the economy on the socially optimal BGP are considerably larger than our initial calibrated level (\(\bar{i}_r^r\) ranges from 24% to 170% of output measured as expenditures on consumption and physical investment as opposed to our baseline level of \(\bar{i}_r = 9.3\%\)). Note that we have assumed that innovation subsidies are financed by lump-sum taxes. Hence we have abstracted from the welfare losses associated to the distortions that would arise if lump sum taxes were unavailable.

These welfare implications are driven by the implications of our model for the long run and our calibration of the gap between the growth rate of output and the interest rate (which implies \(\tilde{\beta} = 0.986\)). Since interest rates are not much higher than the growth rate, households place a high weight on the implications of innovation policies for consumption in the long run. In contrast, if one considers the implications of innovation policies for welfare only over the first 20 years of the transition using the preferences (2) over aggregate consumption but only over periods \(t = 0, \ldots, 20\), this change in welfare over the medium term is actually negative in the two specifications of the model with business stealing.

In this section, we have considered the sensitivity of our measurement of the impact elasticity \(\Theta\) to different estimates of the contribution of entrants’ innovation to productivity growth \(\bar{g}_Z - G(\bar{x}_c, \bar{x}_m, 0)\). Our measurement of \(\Theta_e\) using equation (34) is also sensitive to measurement of the share of innovative investment carried out be entrants \(\bar{x}_e / \bar{Y}_r\). In this paper, we have estimated this share of innovative investment by entrants under the assumption that there investment is not measured in NIPA data for the non-financial corporate sector and instead must be inferred using equations (36) and (37). This measure-
Table 1: Elasticity of aggregate productivity, GDP and welfare with respect to research labor at various time horizons, and optimal innovation intensity
Business stealing ($\delta_c = 0$ or $0.2$), Spillovers ($\phi = -1.6$ or $0.96$)

<table>
<thead>
<tr>
<th>Intertemporal spillovers</th>
<th>No business stealing</th>
<th>With business stealing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low $\phi$</td>
<td>High $\phi$</td>
</tr>
<tr>
<td>Aggregate productivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1: Year 1, $\Theta$</td>
<td>0.026</td>
<td>0.026</td>
</tr>
<tr>
<td>2: Year 20</td>
<td>0.29</td>
<td>0.52</td>
</tr>
<tr>
<td>3: Long run</td>
<td>0.38</td>
<td>25.00</td>
</tr>
<tr>
<td>Aggregate Output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4: Year 0</td>
<td>-0.11</td>
<td>-0.11</td>
</tr>
<tr>
<td>5: Year 20</td>
<td>0.20</td>
<td>0.42</td>
</tr>
<tr>
<td>6: Long run</td>
<td>0.36</td>
<td>33.18</td>
</tr>
<tr>
<td>7: Welfare (equivalent variation)</td>
<td>0.26</td>
<td>2.01</td>
</tr>
<tr>
<td>8: Optimal innovation intensity</td>
<td>0.32</td>
<td>1.70</td>
</tr>
</tbody>
</table>

8 Conclusion

In this paper, we have derived a simple first-order approximation to the transition dynamics of aggregate productivity and output in response to a policy-induced change in the innovation intensity of the economy implied by a model that nests some of the canonical models of growth through firms’ investments in innovation. We see our results as a useful guide to researchers looking to use these models to address quantitative questions regarding the impact of policy induced changes in firms investments in innovation on economic growth.
macroeconomic dynamics and welfare.

As an alternative approach to our model-based approach to measuring the aggregate implications of innovation policies, one might try to directly examine the results of policy changes (see e.g. Bloom et al. 2013). Of course, this may be difficult to do in aggregate data if it would take a very large policy-induced change in the innovation intensity of the economy to bring about a measurable change in aggregate productivity growth as we have found.

In our measurement exercises, we have abstracted from the productivity and welfare gains that might be achieved by reallocating a given level of investment in innovation across different categories of innovative investment. As noted in the discussion to Proposition 6, in the context of our model, one can conduct an analysis of policy changes that favor one category of innovative investment over another if one has information to fix the parameters of the innovative investment technologies \( h(\cdot) \) and \( \zeta(\cdot) \). More complex models in the literature consider a wider array of reasons that the marginal contribution of heterogeneous firms’ innovative investments to aggregate productivity growth might vary across firms. One challenge for research in this area is to find reliable metrics for evaluating which firms should be doing relatively more innovation spending and by how much should these firms increase their investments in innovation.
References


Tyson, Laura and Greg Linden, “The Corporate R&D Tax Credit and U.S. Innovation and Competitiveness; Gauging the Economic and Fiscal Effectiveness of the Credit,” Center for American Progress December 2012.
Appendix

A  Definition of Equilibrium

Here we fill in the details of our definition of equilibrium.

Time is discrete and labeled $t = 0, 1, 2, \ldots$ Let the grid of possible values of the productivity index $z$ be given by $z_n = n\Delta$, for the integers $n$.

An allocation in this model is a sequence of aggregate variables $\{K_t, L_t, L_{pt}, L_{rt}, C_t, Y_t, Y_{rt}, Z_t, M_t\}$, product level variables $\{y_t(z), k_t(z), l_t(z), x_{ct}(z), x_{ml}(z), x_{ct}\}$, and a sequence of measures $\{M_t(z_n)\}$, where $M_t(z_n)$ denotes the measure of intermediate goods in period $t$ with frontier technology for producing that good indexed by $z_n$.

An allocation is feasible if it satisfies equations (1), (3), (4),

$$L_{pt} = \sum z l_t(z) M_t(z),$$

$$K_t = \sum z k_t(z) M_t(z),$$

$$L_{pt} + L_{rt} = L_t,$$

(8) with $Z_t$ given by (6), $M_t = \sum M_t(z)$, and (27) with $x_{ml} \equiv \sum z x_{ml}(z) M_t(z)$ and $x_{ct} \equiv \sum z x_{ct}(z) M_t(z)$. Note that equation (7) is an equilibrium result, not a feasibility condition. To finish the definition of feasibility, we now give a more detailed description of the technologies for innovative investment so as to fully describe the transition law for the measure $M_t(z)$ given in equation (46) below.

Each period, each intermediate good faces probability $\delta_0$ of exiting for exogenous reasons.

In period $t + 1$, entering firms that invested in total $x_{et}$ in period $t$ begin production of a measure $M_{et+1} = x_{et} M_t$ of intermediate goods. A fraction $(1 - \delta_e)$ of these goods are new to society. A fraction $F_e(z_n; Z_{\rho - 1} M_t)$ of these goods that are new to society have productivity index $z_n$. This distribution of productivities for new products in entering firms satisfies

$$\sum_n \exp((\rho - 1)z_n) F_e(z_n; \frac{Z_{\rho - 1} M_t}{M_t}) = \eta_{en} Z_{\rho - 1} M_t.$$  \hspace{1cm} (39)

A fraction $\delta_e$ of these goods are stolen from incumbent firms. Specifically, a good existing at $t$ with productivity index $z_n$ is drawn with probability $M_t(z_n) / M_t$ and an increment of $k > 0$ steps on the grid of productivity indices is drawn from a distribution $J_e(k)$ independent of $n$. The stolen good then has productivity index $z_n + k$ at $t + 1$. This distribution of increments to the productivities for stolen products in entering firms satisfies

$$\sum_k \exp((\rho - 1)k\Delta) J_e(k) = \eta_{es}.$$ \hspace{1cm} (40)

These assumptions imply that the expectation of $\exp((\rho - 1)z)$ for stolen products in
entering firms is given by
\[
\sum_{z_n} \left[ \sum_{k} \exp((\rho - 1)k\Delta) J_e(k) \right] \exp((\rho - 1)z_n) \frac{M_t(z_n)}{M_t} = \eta_{es} \frac{Z_t^{\rho - 1}}{M_t}.
\]

Define the notation
\[
\tilde{M}_{t+1}(z_n) = (1 - \delta_e)x_{ct}M_tF_e(z_n; \frac{Z_t^{\rho - 1}}{M_t}) + \delta_e x_{ct} \sum_k J_e(k) M_t(z_{n-k}).
\] (41)

These assumptions together imply that in the simple model with innovative investment by entering firms only, the evolution of the measure \( M_t(z) \) is given by
\[
M_{t+1}(z_n) = (1 - \delta_{ct})M_t(z_n) + \tilde{M}_{t+1}(z_n),
\]
where \((1 - \delta_{ct}) = (1 - \delta_0 - \delta_e x_{ct})\). We next consider the contribution to the dynamics of the measure \( M_t(z) \) from innovative investment by incumbent firms.

Each product produced by an incumbent firm has associated with it a technology for improving the productivity index \( z \) associated with that product and a technology for acquiring an additional product. There is no technological connection between products, so we treat the innovative investments associated with each product separately.

As specified in the text in section 4, for each existing product at \( t \) with productivity index \( z_n \), there is a technology \( h \left( x_{ml}(z) \frac{Z_t^{\rho - 1}}{\exp((\rho - 1)z)} \right) \) that links the innovative investment \( x_{ml}(z_n) \) associated with that good with the probability that the firm making this investment acquires a new product at \( t + 1 \). Conditional on the incumbent firm acquiring a new product, with probability \((1 - \delta_m)\), this product is new to society and has productivity index \( z_{n+k} \) drawn from distribution \( F_m(k) \), with \( k \) drawn independent of \( n \). This distribution has the property that
\[
\sum_k \exp((\rho - 1)k\Delta) F_m(k) = \eta_{mn}.
\] (42)

With complementary probability \( \delta_m \), the newly acquired product is stolen. In this case, a good that also has productivity index \( z_n \) at \( t \) is stolen, and the firm that steals it draws an increment of \( k > 0 \) steps to the productivity index of that good (giving it productivity index \( z_{n+k} \) at \( t + 1 \)) from a distribution \( J_m(k) \), with \( k \) drawn independent of \( n \). This distribution of increments to the productivities for stolen products in incumbent firms

Appendix 2
satisfies
\[ \sum_k \exp((\rho - 1)k\Delta)\mathcal{J}_m(k) = \eta_{ms}. \] (43)

Define the notation
\[ \tilde{M}_{mt+1}(z_n) = \sum_k [(1 - \delta_m)\mathcal{F}_m(k) + \delta_m\mathcal{J}_m(k)] h \left( x_{mt}(z_{n-k}) \frac{Z_t^{\rho-1}}{\exp((\rho - 1)z_{n-k})} \right) M_t(z_{n-k}). \] (44)

Likewise, for each existing product at \( t \) with productivity index \( z_n \), there is a technology that links the innovative investment \( x_{ct}(z_n) \) associated with that good with the increment to the productivity index of that good at \( t + 1 \) conditional on it not exiting exogenously or being stolen by another firm. Specifically assume that, conditional on investment \( x_{ct}(z_n) \), if the good does not exit exogenously and is not stolen by another firm, then it has new productivity index \( z_{n+k} \), with increment \( k \) (where \( k \) does not need to be positive) drawn from distribution
\[ \mathcal{F}_c \left( k; x_{ct}(z_n) \frac{Z_t^{\rho-1}}{\exp((\rho - 1)z_n)} \right) \]
that satisfies the property that
\[ \sum_k \exp((\rho - 1)k\Delta)\mathcal{F}_c \left( k; x_{ct}(z_n) \frac{Z_t^{\rho-1}}{\exp((\rho - 1)z_n)} \right) = \zeta \left( x_{ct}(z_n) \frac{Z_t^{\rho-1}}{\exp((\rho - 1)z_n)} \right). \]

Define the notation
\[ \tilde{M}_{ct+1}(z_n) = \sum_k \mathcal{F}_c \left( k; x_{ct}(z_{n-k}) \frac{Z_t^{\rho-1}}{\exp((\rho - 1)z_{n-k})} \right) \times \]
\[ \left( 1 - \delta_c x_{ct} - \delta_m h \left( x_{mt}(z_{n-k}) \frac{Z_t^{\rho-1}}{\exp((\rho - 1)z_{n-k})} \right) \right) M_t(z_{n-k}). \] (45)

Given an allocation, the implied transition law defining feasible sequences of measures \( M_t(z) \) then is given by
\[ M_{t+1}(z_n) = \tilde{M}_{ct+1}(z_n) + \tilde{M}_{mt+1}(z_n) + \tilde{M}_{ct+1}(z_n). \] (46)

We define the following prices at time \( t \), in terms of the consumption good, as follows. Let \( W_t \) and \( P_{rt} \) denote the prices at \( t \) of labor and the research good, respectively. Let \( R_{kt} \)
denote the rental rate of physical capital at $t$. Let $p_t(z)$ denote the price at $t$ of an intermediate good with productivity index $z$. Let $MC(R_k, W)$ denote the unit cost function corresponding to the production function $k^{\alpha}l^{1-\alpha}$ (with productivity index $z$ normalized to zero). We define the markup at $t$ on an intermediate good with productivity index $z$ by 
$$\mu_t(z) = \exp(z)p_t(z)/MC(R_k, W_t).$$

We define equilibrium to include a secondary market in the rights to the frontier technology to produce and innovate on an intermediate good. Let $V_t(z)$ denote the price of those rights at $t$ for an intermediate good with index $z$ at $t$. These rights are *cum dividends* in the sense that they include the rights to produce immediately in the current period.

Let $1/(1+R_t)$ denote the price of the consumption good at $t+1$ relative to the consumption good at $t$. Let the price of the consumption good at $t = 0$ be the numeraire. To simplify the notation for intertemporal prices, define $Q_0 = 1$ and $Q_{t+1} = Q_t/(1+R_t)$ for all $t \geq 0$.

Households are endowed with labor $L_t$ in each period $t$ which they can supply either to intermediate goods producing firms to produce current output, $L_{pt}$, or to produce the research good, $L_{rt}$. In period $t = 0$, households are also endowed with ownership of the physical capital stock $K_0$ and of all of the incumbent intermediate goods producing firms. Collectively, these intermediate goods producing firms operate all of the available frontier technologies for producing intermediate goods and hence have value in the aggregate of $\sum V_0(z)M_0(z)$. Households choose consumption $C_t$, next period’s physical capital stock $K_{t+1}$, and investment in entry $x_{et}$ to maximize utility (2) subject to the date zero budget constraints

$$\sum_{t=0}^{\infty} Q_t [C_t + (1-\tau_et)P_{rt}x_{et} + K_{t+1} - (1-\delta_k)K_t - E_t] = R_k0 K_0 + W_0 L_0 + \sum_z V_0(z)M_0(z) +$$

$$\sum_{t=0}^{\infty} Q_{t+1} \left[ \sum_n V_{t+1}(z_n) \tilde{M}_{et+1}(z_n) + R_{kt+1}K_{t+1} + W_{t+1}L_{t+1} \right],$$

where $\tilde{M}_{et+1}(z_n)$ is given as a function of the household’s investment in entry $x_{et}$ as in equation (41).

Final consumption goods producing firm purchase inputs $y_t(z)$ at prices $p_t(z)$ and sell output $Y_t$ determined by equation (4) at price 1. They choose input purchases to maximize profits $(1+\tau_{yt})Y_t - \sum_z p_t(z)y_t(z)$, where $\tau_{yt}$ is a subsidy over the production of the final good, that we introduce to undo the distortion on physical capital accumulation arising from markups.

Research good producing firms hire labor $L_{rt}$ at wage $W_t$ and sell output $Y_{rt}$ deter-
mined by equation (8) at price $P_{rt}$ to maximize profits $P_{rt}Y_{rt} - W_tL_{rt}$.

Intermediate goods producing firms rent physical capital $k_t(z)$ at rental rate $R_{kt}$ and hire production labor $l_t(z)$ at wage $W_t$ to produce output $y_t(z)$ determined by equation (3). These firms are monopolistic competitors that compete in a Bertrand fashion with a latent competitor. Specifically, on each product $z$, firms face a latent competitor who is allowed, under rules of intellectual property, to use technology to produce the same intermediate good with productivity $z - \log \bar{\mu}(z)$. With Bertrand competition, the optimal markup is $\mu(z) = \min \left\{ \frac{\rho}{\rho - 1}, \bar{\mu}(z) \right\}$. The variable profits from production earned on intermediate goods is then

$$\pi_t(z) = \frac{\mu_t(z) - 1}{\mu_t(z)} p_t(z) y_t(z).$$  

(48)

In the simple version of our model with innovative investment only by entering firms, we have that the price of a frontier technology must satisfy

$$V_t(z) = \pi_t(z) + \left( \frac{1 - \delta_{ct}}{1 + R_t} \right) V_{t+1}(z)$$

(49)

where the term $1 - \delta_{ct}$ is determined by the innovative investment of entrants according to $1 - \delta_{ct} = 1 - \delta_0 - \delta_ex_{et}$. 

In the version of our model with innovative investment by incumbent firms, these firms choose innovative investment $x_{mt}(z)$ and $x_{ct}(z)$ to maximize the value of their products. This value maximization problem is given by

$$V_t(z_n) = \max_{x_m, x_c \geq 0} \pi_t(z) - P_{rt} ((1 - \tau_{mt}) x_m + (1 - \tau_{ct}) x_c) +$$

$$\frac{1}{1 + R_t} \sum_k V_{t+1}(z_k) [((1 - \delta_m) F_m(k) + \delta_m J_m(k)) h \left( x_m \frac{Z_t^{\rho - 1}}{\exp((\rho - 1)z_n)} \right) +$$

$$\frac{1}{1 + R_t} \sum_k V_{t+1}(z_k) F_c \left( k; x_c \frac{Z_t^{\rho - 1}}{\exp((\rho - 1)z_n)} \right) (1 - \delta_{ct}(z_n)).$$

The term $(1 - \delta_{ct}(z_n))$ is determined by the innovative investments of other firms according to

$$(1 - \delta_{ct}(z_n)) = 1 - \delta_ex_c - \delta_m h \left( x_{mt}(z_n) \frac{Z_t^{\rho - 1}}{\exp((\rho - 1)z_n)} \right).$$

An equilibrium is a feasible allocation together with prices such that households choose consumption, investment in physical capital and investment in entering firms to maxi-
mize utility subject to their budget constraint (47), final consumption and research good producing firms maximize profits, intermediate goods producing firms maximize variable profits from production as monopolistic competitors, and these intermediate goods producing firms choose innovative investment to maximize the value of their products as in (50).

The socially optimal allocation is the feasible allocation that maximizes household utility.

### B Proofs

When deriving our proofs, we allow for a production subsidy \( \tau_y \) (introduced in Appendix A). We note that with \( \tau_y \not= 0 \), the innovation intensity of the economy is defined as the ratio of innovative investments to firms’ output inclusive of the production subsidy, \( i_{rt} \equiv \frac{P_r Y_{rt}}{(1+\tau_y) Y_t} \).

**Proposition 1** Equation (8) implies that

\[
\log Z'_t - \log Z_t = \frac{1}{1 - \phi} \left[ (\log \bar{Y}'_r - \log \bar{I}_r) - (\log \bar{Y}_r' - \log \bar{Y}_r) \right],
\]

where \( \bar{Y}_r' \) is the use of the research good on the new BGP. Note from equations (27) and (10) that in our simple model with only entry, \( Y_r \) is constant on any BGP so that \( \bar{Y}_r' = \bar{Y}_r \). This proves the result.

**Proposition 2** Log-linearizing equation (10), we obtain

\[
\dot{g}_Z - \bar{g}_Z = \frac{\partial G}{\partial Y_r} \bar{Y}_r (\log Y_{rt} - \log \bar{Y}_r) = \frac{\partial G}{\partial x_e} \bar{Y}_r (\log l'_{rt} - \log \bar{I}_r + (\phi - 1) (\log Z'_t - \log Z_t)) ,
\]

where the second equality uses equation (8). Combining these expressions with the law of motion for aggregate productivity,

\[
(\log Z'_{t+1} - \log Z_{t+1}) = (\log Z'_t - \log Z_t) + \dot{g}_Z - \bar{g}_Z,
\]

we obtain the following AR1 process for deviations of aggregate productivity from BGP,

\[
(\log Z'_{t+1} - \log Z_{t+1}) = (1 + (\phi - 1) \Theta) (\log Z'_t - \log Z_t) + \Theta (\log l'_{rt} - \log \bar{I}_r) ,
\]

Appendix 6
which implies equation (18). This proves the result.

**Corollary 1** If two model economies have the same initial allocation of labor $\bar{l}_p$, then the implied coefficient $\Gamma_0 = \Theta$ is clearly increasing in $\Theta$. If the two models share the same value of intertemporal knowledge spillovers as indexed by $\phi < 1$, then the term $[1 - (1 - \phi)\Theta]$ governing the rate of decay of the coefficients $\Gamma_k$ in equation (19) is decreasing in $\Theta$. This proves the first part of the result. The cumulative sums of coefficients $\Gamma_k$ in the second part of the result are given by

$$\sum_{k=0}^{K} \Gamma_k = \frac{\bar{l}_p}{1 - \phi} \left[ 1 - [1 - (1 - \phi)\Theta]^K \right]$$

which, holding $\phi$ fixed is increasing in $\Theta$ for any finite $K$. This proves the result.

**Lemma 1** This result is obtained by log-linearizing the following equations: equation (7), equation (14), and the equilibrium condition that the rental rate on physical capital be related to the capital output ratio by

$$R_{kt} = (1 + \tau_y) \frac{\alpha Y_t}{\mu K_t}.$$

This proves the result.

**Lemma 2** Let the economy be on an initial BGP with the allocation marked by bars. For any alternative feasible allocation, we have that the equivalent variation is defined by

$$\xi^{1-\eta} \sum_{t=0}^{\infty} (\beta \exp (\eta \bar{g}_L))^t C_t^{1-\eta} = \sum_{t=0}^{\infty} (\beta \exp (\eta \bar{g}_L))^t C_{t}^{1-\eta}.$$ 

Since on a BGP, $\bar{C}_t = \exp (t \bar{g}_Y) \bar{C}_0$, we have

$$\xi^{1-\eta} = (1 - \tilde{\beta}) \sum_{t=0}^{\infty} \tilde{\beta}^t \left( \frac{C_t'}{\bar{C}_t} \right)^{1-\eta},$$

where $\tilde{\beta} = \beta \exp (\eta \bar{g}_L + (1 - \eta) \bar{g}_Y)$. Up to a first-order approximation, around the initial BGP,

$$\log \xi = (1 - \tilde{\beta}) \sum_{t=0}^{\infty} \tilde{\beta}^t (\log C_t' - \log \bar{C}_t). \quad (53)$$

Appendix 7
From the resource constraint of the final consumption good, equation (1), we have, up to a first order approximation,

\[ \log C_t' - \log C_t = \frac{\ddot{Y}_t}{\bar{C}_t} \left[ (\log Z_t' - \log Z_t) + (1 - \alpha) \left( \log l_{pt}' - \log I_p \right) \right] + \frac{\bar{K}_t}{\bar{C}_t} \left[ \left( \alpha \frac{\ddot{Y}_t}{\bar{K}_t} + 1 - d_k \right) (log K_t' - \log \bar{K}_t) - \exp (\ddot{g}_Y) \left( \log K_{t+1}' - \log \bar{K}_{t+1} \right) \right] \]

so

\[ \sum_{t=0}^{\infty} \beta^t (\log C_t' - \log C_t) = \sum_{t=0}^{\infty} \beta^t \frac{\ddot{Y}_t}{\bar{C}_t} \left[ (\log Z_t' - \log Z_t) + (1 - \alpha) \left( \log l_{pt}' - \log I_p \right) \right] + \sum_{t=0}^{\infty} \beta^t \frac{\bar{K}_t}{\bar{C}_t} \left[ \left( \alpha \frac{\ddot{Y}_t}{\bar{K}_t} + 1 - d_k \right) (log K_t' - \log \bar{K}_t) - \exp (\ddot{g}_Y) \left( \log K_{t+1}' - \log \bar{K}_{t+1} \right) \right] \]

At \( t = 0 \), \( \log K_0' = \log \bar{K}_0 \) and, on any BGP in which the Euler equation for physical capital is undistorted (which can be achieved by setting \( \tau_{yt} = \bar{\tau}_y = \mu - 1 \)), we have

\[ \exp (\ddot{g}_Y) = \ddot{\beta} \left( \alpha \frac{\ddot{Y}_t}{\bar{K}_t} + 1 - d_k \right) \]

Hence

\[ \sum_{t=0}^{\infty} \beta^t (\log C_t' - \log C_t) = \sum_{t=0}^{\infty} \beta^t \frac{\ddot{Y}_t}{\bar{C}_t} \left[ (\log Z_t' - \log Z_t) + (1 - \alpha) \left( \log l_{pt}' - \log I_p \right) \right] . \]

Given this result in combination with (53) we obtain equation (22).

**Proposition 3** Let \( \bar{W}_t^* \) denote the relative price of labor and the final consumption good and \( \bar{P}_{rt}^* \) the relative price of the research good and the final consumption good applied by the social planner on the BGP of the socially optimal allocation. In the socially optimal allocation, the price of labor equals its value marginal product in each sector, so

\[ \bar{W}_t^* = (1 - \alpha) \frac{\ddot{Y}_t^*}{\bar{L}_{pt}^*} = \frac{\ddot{P}_{rt}^* \ddot{Y}_r^*}{\bar{L}_{rt}^*} \]

and thus the innovation intensity on the BGP of the socially optimal allocation is related to the allocation of labor in that allocation by

\[ \ddot{r}_r^* = (1 - \alpha) \frac{\bar{I}_r^*}{l_r^*} . \]

Appendix 8
The allocation of labor between research and production on the socially optimal allocation is set so that the welfare gains in equation (23) from perturbations to the innovation intensity of the economy are equal to zero. This delivers the result in equation (24).

**Proposition 4** To prove this result, we use the zero profits at entry condition to show that total post subsidy expenditure on innovative investment relative to output \((1 - \tau_c)\bar{s}_r\) is constant across balanced growth paths. We first develop that zero profits at entry condition and then apply conditions that hold across all balanced growth paths to prove the result. We proceed as follows.

Under the assumption that markups are constant across products and dates \((\mu_t(z) = \mu)\), we have that variable profits are given by

\[
\pi_t(z) = (1 + \tau_y) \frac{\mu - 1}{\mu} Y_t s_t(z).
\] (54)

From equation (49), we have that the price of a product \(V_t(z)\) is directly proportional to the size of the product \(s_t(z)\), where the factor of proportionality is given by \(V_t\) which satisfies

\[
V_t = (1 + \tau_y) \frac{\mu - 1}{\mu} Y_t + \frac{(1 - \delta_{ct})}{1 + R_t} V_{t+1}.
\] (55)

With prices for products proportional to the size of products, the first order conditions for the household’s optimal choice of \(x_{et} \geq 0\) together with equations (39), (40), and (41) imply that

\[
(1 - \tau_{et}) \frac{P_{rt}}{M_t} \geq \frac{1}{1 + R_t} V_{t+1} \eta_e \frac{Z_{t+1}^{\mu - 1}}{M_t Z_{t+1}^{\mu - 1}}.
\] (56)

with this expression holding as an equality if \(x_{et} > 0\). This condition (56) corresponds to the condition that the household earn non-positive profits from investment in entry.

On a BGP, the value \(v_t = V_t / ((1 + \tau_y) Y_t)\) is constant over time at \(\bar{v}\) and equation (55) implies

\[
\bar{v} = \left(\frac{\mu - 1}{\mu}\right) \left[1 - \exp(\bar{g}_Y) \frac{1 - \bar{\delta}_c}{1 + R} \exp((\rho - 1)\bar{g}_Z)\right]^{-1},
\]

where \(1 - \bar{\delta}_c = 1 - \delta_0 - \delta_c \bar{x}_c\) is the exit rate of existing products on the BGP. Dividing both sides of (56) by \(Y_t\) implies that on a BGP, we obtain

\[
(1 - \tau_e) \frac{\bar{i}_r}{\bar{Y}_r} = \exp(\bar{g}_Y) \frac{\eta_e}{1 + R} \left(\frac{\mu - 1}{\mu}\right) \left[1 - \exp(\bar{g}_Y) \frac{1 - \bar{\delta}_c}{1 + R} \exp((\rho - 1)\bar{g}_Z)\right]^{-1}.
\]

Appendix 9
With semi-endogenous growth \( (\phi < 1) \), \( \bar{g}_Y, \bar{g}_Z \), and \( \bar{R} \) are constant across BGPs. By the resource constraint \( \bar{Y}_r = \bar{x}_e \) and equation (11), \( \bar{Y}_r \) is also constant across BGPs. This implies that
\[
\bar{t}_{rt}(1 - \bar{e}_e) = \bar{t}_{rt}'(1 - \bar{e}_e')
\]
and
\[
\frac{\bar{E}'_t}{\bar{Y}'_t} - \frac{\bar{E}_t}{\bar{Y}_t} = \bar{e}_e\bar{t}_{rt}' - \bar{e}_e\bar{t}_{rt} = \bar{t}_{rt}' - \bar{t}_{rt}.
\]
This proves the result.

**Lemma 3** Conjecture that in equilibrium incumbent firms scale their investment in innovation to acquire new products and improve their existing products in proportion to the size of these existing products, i.e.
\[
x_{mt}(z) = x_{mt}s_t(z)
\]
and
\[
x_{ct}(z) = x_{ct}s_t(z).
\]
We first show that equation (28) holds under this conjecture and then verify the conjecture holds in equilibrium.

Under the conjecture that investment by incumbent firms in acquiring new products scales with product size, given the investment technology for incumbent firms to acquire new products specified in subsection 4.1 above, the probability that an incumbent firm producing a product with index \( z \) at \( t \) acquires a new product for the firm at \( t + 1 \) is \( h(x_{mt}) \), independent of the index \( z \) of that product. Hence, incumbent firms acquire in the aggregate measure \( h(x_{mt})M_t \) new products — a measure \( \delta_m h(x_{mt})M_t \) are stolen from other incumbent firms and complementary measure \( (1 - \delta_m) h(x_{mt})M_t \) are new to society. From equations (42) and (43), for existing products with productivity \( z \), these newly acquired products have average value of \( \exp((\rho - 1)z') \) equal to \( \eta_{mn} \exp((\rho - 1)z) \) and \( \eta_{ms} \exp((\rho - 1)z) \), respectively. Averaging across all existing products at \( t \) then gives that the average value of \( \exp((\rho - 1)z') \) across all newly acquired products in incumbent firms at \( t + 1 \) is given by
\[
\eta_m \sum_z \exp((\rho - 1)z) \frac{M_t(z)}{M_t} = \eta_m \frac{Z^\rho - 1}{M_t}.
\]
Given the investment technology for incumbent firms to improve existing products specified in subsection 4.2, if investment in improving existing products scales with product size, then the transition probabilities for the index \( z \) at \( t \) to \( z' \) at \( t + 1 \) for products
produced by the same incumbent firm at $t$ and $t+1$ are as follows. Of the $M_t$ existing products in incumbent firms at $t$, a measure $\delta_0 M_t$ are lost to exogenous exit, a measure $\delta_m h(x_{mt}) M_t$ are lost to business stealing by other incumbent firms, and a measure $\delta_e M_{ct} = \delta_e x_{ct} M_t$ are lost to business stealing by entering firms. The products that exit at $t$ for either exogenous or endogenous reasons have productivity indices $z$ at $t$ drawn uniformly from the current distribution of these productivity indices $M_t(z)/M_t$. The measure $(1 - \delta_0 - \delta_m h(x_{mt}) - \delta_e x_{ct}) M_t$ of existing products that continue with the same incumbent firm from $t$ to $t+1$ each experience expected growth in $\exp((\rho - 1)z')$ from $t$ to $t+1$ of $\zeta(x_{ct})$. That is, averaging across products that do not exit gives that the average value of $\exp((\rho - 1)z')$ at $t+1$ for all products that are produced by the same firm at $t$ and $t+1$ is given by

$$\zeta(x_{ct}) \frac{Z_t^{\rho - 1}}{M_t}$$

and the fraction of products at $t$ that are in this category at $t+1$ is

$$1 - \delta_{ct} = 1 - \delta_0 - \delta_m h(x_{mt}) - \delta_e x_{ct}.$$

(57)

Putting these results together gives that the value of $Z_{t+1}^{\rho - 1}$ is a sum of three components

$$Z_{t+1}^{\rho - 1} = (1 - \delta_{ct}) M_t \zeta(x_{ct}) \frac{Z_t^{\rho - 1}}{M_t} + h(x_{mt}) M_t \eta_m \frac{Z_t^{\rho - 1}}{M_t} + x_{ct} M_t \eta_e \frac{Z_t^{\rho - 1}}{M_t}$$

where the first term is the measure of continuing products in incumbent firms times the average value of $\exp((\rho - 1)z')$ for such products, the second term is the product of the measure of new products in incumbent firms times the average value of $\exp((\rho - 1)z')$ for such products, and the third term is the corresponding measure of new products in entering firms times the average value of $\exp((\rho - 1)z')$ for such products. Taking logs of this expression gives equation (28).

To complete the proof, we must show that in equilibrium firms actually choose to scale their innovative investments in proportion to the size of the products those investments are associated with. We do so as follows.

Since markups are constant across products and time, we again have variable profits given by equation (54). Under the conjecture that incumbent firms’ innovative investments scale with size, then the equilibrium value function $V_t(z)$ in equation (50) also
scales with size with \( V_t(z) = V_t s_t(z) \). In particular, \( V_t \) satisfies

\[
V_t = \max_{x_m,x_c \geq 0} (1 + \tau_y) \left( \frac{H - 1}{\mu} Y_t - Pr_t \left( (1 - \tau_{mt}) x_m + (1 - \tau_{ct}) x_c \right) + \right.
\]

\[
\left. \frac{1}{1 + R_t} V_{t+1} \left[ \eta_m h'(x_m) + (1 - \delta_{ct}) \zeta'(x_{ct}) \right] Zt^\rho - 1 \bigg) \bigg] \frac{Zt^\rho - 1}{Zt_{t+1}^\rho - 1}. \]

With this form for \( V_t(z) = V_t s_t(z) \), we have that the first order conditions of the incumbent firm’s profit maximization problem (50) with respect to \( x_m \) and \( x_c \) imply that the optimal choice of \( x_{ct} \) and \( x_{mt} \) both scale with the size of the product.

Note that the zero profits at entry condition is still given by equation (56). This proves the result.

**Lemma 4** Let \( \bar{x}_c, \bar{x}_m \), and \( \bar{x}_e \) denote the allocation of innovative investment on a BGP and \( \bar{Y}_r \) aggregate real innovative investment. At this allocation of innovative investment, the values of \( \Theta_i \) are given by

\[
\Theta_c = \frac{1}{\rho - 1} \frac{(1 - \bar{\delta}_c) \zeta'(\bar{x}_c)}{\exp((\rho - 1) \bar{g} z)} \bar{Y}_r, \tag{59}
\]

\[
\Theta_m = \frac{1}{\rho - 1} \frac{(\eta_m - \delta_m \zeta'(\bar{x}_c)) h'(\bar{x}_m)}{\exp((\rho - 1) \bar{g} z)} \bar{Y}_r, \tag{60}
\]

\[
\Theta_e = \frac{1}{\rho - 1} \frac{(\eta_e - \delta_e \zeta'(\bar{x}_c))}{\exp((\rho - 1) \bar{g} z)} \bar{Y}_r. \tag{61}
\]

Our assumptions imply that \((1 - \bar{\delta}_c) > 0, \eta_m > \delta_m \zeta(\bar{x}_c), \) and \( \eta_e > \delta_e \zeta(\bar{x}_c) \), which implies that \( \Theta_i > 0 \).

To rank the values of \( \Theta_i \), observe that the first order conditions of (58) with respect to \( x_c \) and \( x_m \) imply that

\[
(1 - \tau_{ct}) P_{rt} \geq \frac{1 - \delta_{ct}}{1 + R_t} V_{t+1} \zeta'(x_{ct}) \frac{Zt^\rho - 1}{Zt_{t+1}^\rho - 1} \tag{62}
\]

and

\[
(1 - \tau_{mt}) P_{rt} \geq \frac{\eta_m}{1 + R_t} V_{t+1} h'(x_{mt}) \frac{Zt^\rho - 1}{Zt_{t+1}^\rho - 1}. \tag{63}
\]

These first order conditions are equalities if \( x_{ct}, x_{mt} > 0 \). These first order conditions together with the zero profits at entry condition (56) imply that if the allocation of invest-
ment in period $t$ is interior, then

$$\frac{(1 - \tau_{ct})}{(1 - \tau_{ct})} \eta_e = (1 - \delta_{et}) \xi'(x_{ct})$$  \hspace{1cm} (64)$$

and

$$\frac{(1 - \tau_{mt})}{(1 - \tau_{ct})} (1 - \delta_{ct}) \xi'(x_{ct}) = \eta_m h' (x_{mt})$$  \hspace{1cm} (65)$$

If, on the initial BGP, $\tau_e \geq \tau_c$, then $\eta_e \leq (1 - \delta_c) \xi'(\bar{x}_c)$. Since $\eta_e - \delta_e \zeta(\bar{x}_c) \leq \eta_e$, this proves $\Theta_e F \leq \Theta_c$. Likewise, if, on the initial BGP, $\tau_m \geq \tau_c$, then $\eta_m h' (\bar{x}_m) \leq (1 - \delta_c) \xi'(\bar{x}_c)$. Since $\eta_m - \delta_m \zeta(\bar{x}_c) \leq \eta_m$, this proves $\Theta_m \leq \Theta_c$.

**Lemma 5** Let $\bar{x}_c$, $\bar{x}_m$, and $\bar{x}_e$ be an interior equilibrium allocation of investment on an initial BGP corresponding to policies $\tau_c$, $\tau_m$, and $\tau_e$. We now examine the conditions under which this equilibrium allocation of innovative investment is a solution to this cost minimization problem (31).

Because the allocation of innovative investment on the initial BGP is interior, it satisfies equations (64) and (65) at the specified policies. Moreover, on a BGP, we must have that the growth rate of aggregate productivity is given by

$$\bar{g}_Z = G(\bar{x}_c, \bar{x}_m, \bar{x}_e).$$  \hspace{1cm} (66)$$

Compare these first order conditions to those characterizing a conditionally efficient allocation of innovative investment. An interior allocation of innovative investment is a solution to the cost minimization problem (31) if equation (66) is satisfied and

$$\frac{\partial}{\partial x_m} G(\bar{x}_c, \bar{x}_m, \bar{x}_e) = \frac{\partial}{\partial x_c} G(\bar{x}_c, \bar{x}_m, \bar{x}_e) \iff (\eta_m - \delta_m \zeta(\bar{x}_c)) h'(\bar{x}_m) = \eta_e - \delta_e \zeta(\bar{x}_c)$$  \hspace{1cm} (67)$$

and

$$\frac{\partial}{\partial x_c} G(\bar{x}_c, \bar{x}_m, \bar{x}_e) = \frac{\partial}{\partial x_e} G(\bar{x}_c, \bar{x}_m, \bar{x}_e) \iff (1 - \delta_0 - \delta_m h(\bar{x}_m) + \delta_e \bar{x}_e) \xi'(\bar{x}_c) = \eta_e - \delta_e \zeta(\bar{x}_c).$$  \hspace{1cm} (68)$$

These first-order conditions coincide with the equilibrium conditions (64) and (65) if

$$\frac{(1 - \tau_c)}{(1 - \tau_e)} = \frac{\eta_e - \delta_e \zeta(x^e)}{\eta_e}$$  \hspace{1cm} (69)$$
and
\[
\frac{(1 - \tau_m)}{(1 - \tau_e)} = \frac{\eta_m}{\eta_e} \left( \frac{\eta_e - \delta_c \zeta(x_e^*)}{\eta_m - \delta_m \zeta(x_e^*)} \right).
\] (70)

Hence, if (i) \( \delta_e = \delta_m = 0 \) and/or (ii) \( \delta_e = \delta_m > 0 \), \( \zeta(x_e^*) = \tilde{\zeta} \) and \( \eta_m = \eta_e \), the equilibrium BGP is conditionally efficient if policies are uniform, that is \( \frac{(1 - \tau_c)}{(1 - \tau_e)} = \frac{(1 - \tau_m)}{(1 - \tau_e)} = 1 \).

Now consider the problem of finding policies to implement a conditionally efficient allocation of innovative investment \( x_e^*, x_m^*, x_c^* \) as an equilibrium outcome with \( Y_r^* \) equal to the aggregate of these three categories of innovative investment. To do so, set the ratios of subsides \( (1 - \tau_c)/(1 - \tau_e) \) and \( (1 - \tau_m)/(1 - \tau_e) \) as in equations (69) and (70). To complete the construction of equilibrium, we must find the level of subsidies \( \tau_e \) together with the constant in the value function \( \bar{\sigma} \) and the BGP ratio of the relative price of the research good to output \( \tilde{P}_r/(1 + \tau_y) \bar{Y} \) that satisfy the BGP version of equation (58) given by
\[
\bar{\sigma} = \left[ \frac{\mu - 1}{\mu} - (1 - \tau_e) \frac{\bar{P}_r}{(1 + \tau_y) \bar{Y}} \left( \frac{1 - \tau_e}{1 - \tau_c} x_e^* + \frac{1 - \tau_m}{1 - \tau_c} x_m^* \right) \right] \times
\]
\[
\left[ 1 - (1 - \delta_0 - \delta_m h(x_m^*) - \delta_c x_e^*) \zeta(x_e^*) \frac{\exp(\tilde{g}_Y - (\rho - 1)\tilde{g}_Z)}{1 + \tilde{R}} \right]^{-1}
\]
as well as the BGP version of the zero profits at entry condition (56)
\[
(1 - \tau_e) \frac{\bar{P}_r}{(1 + \tau_y) \bar{Y}} = \eta_e \frac{\exp(\tilde{g}_Y - (\rho - 1)\tilde{g}_Z)}{1 + \tilde{R}} \bar{\sigma}.
\] (72)

It is straightforward to show that a unique positive solution of these two equations for \( \bar{\sigma} \) and \( (1 - \tau_e) \bar{P}_r/\bar{Y} \) exists since the solution of \( \bar{\sigma} \) in equation (71) is strictly decreasing in \( (1 - \tau_e) \bar{P}_r/\bar{Y} \). The equilibrium level of aggregate productivity is then found as function of the choice of entry subsidy \( \tau_e \) as follows. From equation (8), we have
\[
x_e^* + x_m^* + x_c^* = Y_r^* = A_{rt} Z_{t}^{\phi -1} L_{rt}
\]
Equation (13) implies
\[
\frac{P_{rt}}{Y_t} = \frac{W_t}{Y_t} \left( \frac{1}{A_{rt} Z_{t}^{\phi -1}} \right) = \frac{W_t L_{rt}}{Y_t Y_r^*}.
\]

Using the fact that the production labor share of output is given by \( W_t L_{pt} = (1 + \tau_y) \frac{1 - \alpha}{\mu} Y_t \), we then have
\[
\frac{P_{rt}}{(1 + \tau_y) Y_t} = \frac{1 - \alpha}{\mu} \frac{1}{Y_t} \frac{L_{rt}}{L_{pt}}.
\]
Thus, since the equilibrium value of $(1 - \tau_e)\frac{P_t}{Y_t}$ is pinned down by the free entry condition, a choice of entry subsidy $\tau_e$ determines $\frac{P_t}{Y_t}$. This, together with the labor market clearing condition $L_{pt} + L_{rt} = L_t$, gives the solution for the equilibrium allocation of labor to research $L_{rt}^*$ and thus the level of aggregate productivity relative to exogenous scientific progress $A_t Z_t^{\phi-1}$ on the BGP.

This proves the result.

**Proposition 5** To prove this proposition, we use the following results.

First observe that equation (14) holds in our extended model. Second, log-linearizing equation (28), we obtain

$$g_Zt - \bar{g}_Z \approx \Theta_c \frac{\bar{x}_c}{Y_r} \left( \log x'_{ct} - \log \bar{x}_c \right) + \Theta_m \frac{\bar{x}_m}{Y_r} \left( \log x'_{mt} - \log \bar{x}_m \right) + \Theta_e \frac{\bar{x}_e}{Y_r} \left( \log x'_{et} - \log \bar{x}_e \right),$$

where these derivatives are evaluated at the initial BGP allocation. From the resource constraint for the research good, we have

$$\frac{\bar{x}_c}{Y_r} \left( \log x'_{ct} - \log \bar{x}_c \right) + \frac{\bar{x}_m}{Y_r} \left( \log x'_{mt} - \log \bar{x}_m \right) + \frac{\bar{x}_e}{Y_r} \left( \log x'_{et} - \log \bar{x}_e \right) = \left( \log Y'_{rt} - \log \bar{Y}_r \right).$$

The first-order conditions of the minimization problem that defines $\bar{Y}_r^*$ imply that, in a conditionally efficient allocation, $\Theta_c = \Theta_m = \Theta_e$. Thus,

$$g_Zt - \bar{g}_Z \approx \Theta \left( \log Y'_{rt} - \log \bar{Y}_r \right) \quad (73)$$

where $\Theta = \Theta_c = \Theta_m = \Theta_e$. The proof of proposition (2) then follows as before. Lemmas 1 and 2 also follow using the same proofs as before.

The result that proposition 1 holds to a first order approximation is shown as follows. Using equations (8) and (73), the growth rate of productivity between periods $t$ and $t + 1$ is given by

$$g_Zt - \bar{g}_Z \approx \Theta \left( \log l'_{rt} - \log \bar{l}_r + (\phi - 1) \left( \log Z'_i - \log Z_t \right) \right). \quad (74)$$

Recall that if $\phi < 1$, the growth rate of aggregate productivity is constant on all BGPs. Thus, following any change in innovation policies, when the economy converges to a new BGP it has the same growth rate of productivity as it had on the initial BGP. Substituting $g_Zt - \bar{g}_Z = 0$ in equation (74) gives equation (15) as a first order approximation.

To see that (15) is an upper bound on the change in productivity from the initial BGP to the new BGP for any policy change resulting in a change in the allocation of labor of size $\log l'_r - \log \bar{l}_r$ across BGPs, recall that the change in productivity across BGPs is given by

Appendix 15
equation (51). Since the initial BGP is conditionally efficient, we have that \( \bar{Y}_r \) minimizes the amount of the research good needed to attain the BGP growth rate \( \bar{g}_Z \) and hence the term \( \bar{Y}_r - \bar{Y}_r \geq 0 \).

We prove the bound on the impact elasticity in equation (26) as follows. Consider first a policy-induced change in the innovation intensity of the economy in which all three types of innovative investment are increased proportionately, so that

\[
\log x'_{ct} - \log \bar{x}_c = \log x'_{ml} - \log \bar{x}_m = \log x'_{et} - \log \bar{x}_e = \log Y'_{rt} - \log \bar{Y}_r.
\]

In this case, we can prove that the impact elasticity \( \Theta \) associated with this particular perturbation of innovative investment has an upper bound given by equation (26). The proof of this point follows from the concavity of the function \( F(a) \) defined as

\[
F(a) \equiv G(a\bar{x}_c, a\bar{x}_m, a\bar{x}_e).
\]

Note that

\[
F'(1) = \frac{\partial G}{\partial x_c} \frac{\bar{x}_c}{\bar{Y}_r} + \frac{\partial G}{\partial x_m} \frac{\bar{x}_m}{\bar{Y}_r} + \frac{\partial G}{\partial x_e} \frac{\bar{x}_e}{\bar{Y}_r}
\]

so that

\[
F'(1) = \Theta_c \frac{\bar{x}_c}{\bar{Y}_r} + \Theta_m \frac{\bar{x}_m}{\bar{Y}_r} + \Theta_e \frac{\bar{x}_e}{\bar{Y}_r}.
\]

Hence, \( F'(1) \) is the value of \( \Theta \) corresponding to a change in policies such that the change in each component of innovative investment is directly proportional to the change in the aggregate \( Y_r \), i.e. the terms \( dx_i/dY_r = \bar{x}_i/\bar{Y}_r \) in equation (30). If \( F(a) \) is concave, we have \( F'(1) \leq F(1) - F(0) \). From the definition of \( F(a) \), we have that \( F(1) - F(0) = \bar{g}_Z - G^0 \). This proves that our bound on \( \Theta \) given by (26) holds for policy changes that result in proportional changes in the components of real innovative investment whenever \( F(a) \) is concave.

When the initial BGP is conditionally efficient, we have that the value of \( \Theta \) is independent of how the policy induced change in \( Y_r \) is allocated across components of aggregate investment so we have that \( F'(1) = \Theta \) for any policy change.

We prove that the function \( F \) is concave as follows. The assumptions made above that \( \eta_{es} > \zeta(\bar{x}_c) \) and \( \eta_{ms} > \zeta(\bar{x}_c) \) together with the assumptions that \( \eta_{en}, \eta_{mn} > 0 \) imply that \( \eta_m - \delta \zeta(\bar{x}_c) > 0 \) and \( \eta_e - \delta \zeta(\bar{x}_c) > 0 \). These inequalities, together with the assumptions that the functions \( \zeta(\cdot) \) and \( h(\cdot) \) and \( \log(\cdot) \) are all strictly concave, imply that the function \( F(a) \) is concave.

This proves the result.
Proposition 6  Under the assumption that the new BGP allocation of real innovative investment is interior, first order conditions (64) and (65) hold as equalities at that allocation $\bar{x}'_c, \bar{x}'_m, \bar{x}'_e$, and aggregate real innovative investment $\bar{Y}'_t$ is given by equation (27) at that allocation. If the allocation of innovative investment remains interior on the transition from the initial BGP to the new BGP, then, since the new policies satisfy condition (32), these same equations are satisfied by the allocation of innovative investment $x'_ct, x'_mt, x'_et$ and $Y'_t$ in each period $t \geq 0$ of the transition.

We obtain the expressions for $dx_c / dY_r, dx_m / dY_r$, and $dx_e / dY_r$ given in the statement of the proposition by differentiating these three equations, evaluating these derivatives at the new BGP allocation of innovative investment. Specifically, the result that $dx_m / dY_r = 0$ is obtained by combining equations (64) and (65) to obtain

$$\frac{(1 - \tau_{ct})}{(1 - \tau_{et})} \eta_e = \eta_m h'(x_{mt}).$$

This observation implies that if $\delta_e = 0$, then, from equation (64), $dx_c / dY_r = 0$ as well, since $x_{mt} = \bar{x}'_m$ in every period $t$ of the transition to the new BGP. In this case $dx_e / dY_r = 1$ and $\Theta = \Theta_e$.

More generally, we have

$$\Theta' = \Theta'_c + \frac{dx_c}{dY_r} (\Theta'_c - \Theta'_e),$$

(75)

where

$$\frac{dx_c}{dY_r} = \left[ \frac{\delta_e \zeta'(\bar{x}'_c)}{(1 - \delta_0 - \delta_m h(\bar{x}'_m) - \delta_e \bar{x}'_e) \zeta''(\bar{x}'_c)} \right] \left[ 1 + \frac{\delta_e \zeta'(\bar{x}'_c)}{(1 - \delta_0 - \delta_m h(\bar{x}'_m) - \delta_e \bar{x}'_e) \zeta''(\bar{x}'_c)} \right]^{-1}.$$

For values of $\delta_e > 0$ but close to zero, we have $dx_c / dY_r < 0$. As a result, given our restrictions on policies in Lemma 4, we have $\Theta'_c \geq \Theta'_e$ and thus $\Theta' \leq \Theta'_e$. We must place bounds on $\delta_e$ to ensure that three inequalities hold: $(1 - \delta'_c) = (1 - \delta_0 - \delta_m h(\bar{x}'_m) - \delta_e \bar{x}'_e) > 0,$

$$1 + \frac{\delta_e \zeta'(\bar{x}'_c)}{(1 - \delta'_c) \zeta''(\bar{x}'_c)} > 0$$

and $\Theta' > 0$. All three of these inequalities hold when $\delta_e = 0$. By continuity, there is an interval of positive values of $\delta_e$ for which all three of these inequalities continue to hold.

Proposition 7  Under the assumption that the new BGP allocation of real innovative investment on the initial BGP is interior, first order conditions (64) and (65) hold as equal-
ities at this allocation and the growth rate of aggregate productivity is given by (28) with $g_Z = \bar{g}_Z$. The corresponding level of $\bar{Y}_r$ is given by equation (27). If the policies on the new BGP satisfy (33), then these equations are unchanged on the new BGP and hence the allocation of real innovative investment is the same on the old and the new BGP. The proof that proposition 1 holds then follows the original proof given that we have shown that aggregate innovative investment $\bar{Y}_r$ is unchanged by policies across the initial and final BGP. The proof that the dynamics of aggregate productivity are given as in Proposition 2 is a direct application of Proposition 6.

**Corollary 2** From Proposition 6, we have that $dx_e/dY_r > 1$ and $dx_c/dY_r < 0$. Since the sum of these two terms is one, it is immediate that $\Theta \leq \Theta_e$ if $\Theta_c \geq \Theta_e$. From Lemma 4, we have that $\Theta_c \geq \Theta_e$ when initial policies are uniform and the initial allocation of innovative investment is interior. This proves the result.

**Measuring impact elasticities** By equation (61)

$$\Theta_e = \frac{1}{\rho - 1} \left( \frac{\eta_e - \delta_e \zeta (\bar{x}_c)}{\bar{s}_e} \right) \bar{Y}_r$$

Given the definition of $G$ in (28), we have that

$$\exp(G(\bar{x}_c, \bar{x}_m, \bar{x}_e))^{\rho - 1} - \exp(G(\bar{x}_c, \bar{x}_m, 0))^{\rho - 1} = (\eta_e - \delta_e \zeta (\bar{x}_c)) \bar{x}_e$$

which combined with equation (76) implies equation (34). We can also express $\Theta_e$ as

$$\Theta_e = \frac{1}{\rho - 1} \left( 1 - \frac{\bar{s}_e}{\bar{s}_{size_e}} \right) \bar{Y}_r, \quad \bar{s}_e = \frac{\eta_e \bar{x}_c}{\exp(\bar{g}_Z)^{\rho - 1}}$$

where we used

$$\frac{av\text{size}_c}{av\text{size}_e} = \frac{\zeta (\bar{x}_c)}{\eta_e}$$

where $av\text{size}_c$ denotes the average size of continuing products and $av\text{size}_e$ denotes the average size of new products acquired by entering firms. Therefore, given a target for the term in square brackets in equation (34), and given data on $av\text{size}_e$ and $\bar{s}_e$ we can back out the implied level of $\delta_e$.

By equations (59) and (64),
\[ \Theta_c = \left[ 1 - \bar{\tau}_c \right] \left[ 1 - \frac{1}{1 - \delta^e_{avsize_c}} \right] \Theta_c = \left[ 1 - \bar{\tau}_c \right] \left[ \frac{1 + \bar{R}}{\rho - 1} \right] \frac{\bar{i}_r}{\bar{v}}, \]  

(78)

where the second equality uses equations (37) and (77). Therefore, the value of \( \Theta_c \) is independent of the extent of business stealing \( \delta_c \) or of the assumed contribution of entrants to productivity growth.

Finally, by equations (60), (64) and (65)

\[ \Theta_m = \left[ 1 - \bar{\tau}_m \right] \left[ 1 - \delta^m_{avsize_m} \frac{avsize_m}{avsize_m} \right] \Theta_e = \left[ 1 - \bar{\tau}_c \right] \left[ 1 - \delta^e_{avsize_c} \right] \Theta_c, \]  

(79)

where the second equation uses equation (78).

\section*{C Quantitative Analysis}

Section C.1 provides additional details of the calibration procedure for our analytic elasticities. Section C.2 describes how we calibrate additional parameters that are required to solve the model non-linearly. Section C.3 provides the equations that are used to solve for a BGP. Section C.4 describes how to solve for the transition dynamics. Section C.5 provided figures that complement our results in Section 7.

\subsection*{C.1 Data and calibration}

We set the time period in the model to one year and calibrate the BGP of the model using average data for the period 1990-2014 (whenever possible).

We first describe how we assign values to the parameters determining the elasticities required to evaluate the aggregate implications of a change in innovation policies. We then describe how we parameterize the model to evaluate the full non-linear dynamic.

The parameters and BGP statistics that we need to assign to calculate our elasticities analytically are: the degree of intertemporal knowledge spillovers \( \phi \), the impact elasticity \( \Theta \), the share of physical capital in costs \( \alpha \), the share of production labor in firms’ output (inclusive of production subsidies) \( \frac{(1-\alpha)}{\mu} \), the share of innovative investment in firms’ output (inclusive of production subsidies) \( \bar{i}_r \), the discount factor (which equals the ratio of the output growth rate to the interest rate, \( \bar{\beta} = \frac{\exp(\bar{g}_Y)}{1 + \bar{R}} \)), the parameter governing the intertemporal elasticity of substitution \( \eta \), consumption to output ratio \( \frac{\bar{C}}{\bar{Y}} \), and the depreciation rate of physical capital \( d_k \) (which is required to calculate the dynamics of the rental
rate \( R_L \). We set \( \Theta \) equal to its upper bound, \( \Theta_e \). To measure \( \Theta_e \), we use expression (34), which requires assigning values to the elasticity of substitution \( \rho \), the baseline productivity growth rate \( \tilde{g}_Z \) (which, given \( \alpha \) and \( \tilde{g}_Y \), requires a value for the growth rate of the labor force \( \tilde{g}_L \)), the counterfactual growth rate when investment by entrants is set to zero \( G(\tilde{x}_e, \tilde{x}_m, 0) \), and the ratio of innovative investments by entrants to total investments \( \frac{\tilde{x}_e}{L} \).

To measure \( \frac{\tilde{x}_e}{L} \) we use equation (36) (together with 36 and 37), which require measures of dividends relative to output \( \tilde{d} \), employment shares of entering firms \( \tilde{s}_e \), and innovation subsidy rates for investment by entrants \( \tau_e \). We also require initial BGP values for the innovation subsidies for incumbent firms, \( \tau_c \) and \( \tau_m \), and the production subsidy (which we set to undo the distortions on capital accumulation arising from markups and the corporate profits tax). In measuring the rental rate of capital and firm dividends, we introduce a corporate profits tax which we denote by \( \tau_{corp} \). In what follows, we describe how we assign values to these parameters and targets, which are reported in Table 2.

As described in the text, we consider two values of \( \phi \): \( \phi = -1.6 \) and \( \phi = 0.96 \). We set the elasticity of substitution \( \rho \) to 4 in the CES aggregator in equation 4. Note that this assumption fixes the term \( 1/(\rho - 1) \) that enters into our impact elasticity formulas. Holding the equilibrium markup \( \mu \) fixed, changes in this parameter \( \rho \) have no impact on any other implication of our model for the elasticities of aggregate productivity and welfare with respect to changes in aggregate innovative investment other than through this term. Hence, it is clear that our measured elasticities will be larger if we choose a value of \( 1 < \rho < 4 \) and smaller if we choose a value of \( \rho > 4 \).

We set the intertemporal elasticity parameter \( \eta \to 1 \) (i.e. log utility) and fix a BGP consumption interest rate of \( \bar{R} = 4\% \). This rate of return is close to that estimated by Poterba (1998) (5.1\%), Hall (2003) (4.46\%), and by McGrattan and Prescott (2005b) (4.1\% for 1990-2001). We have set it at the low end of these estimates to reflect the decline in real interest rates that has occurred over the past several decades. We set the growth rate of the labor force \( \tilde{g}_L = 0.008 \) corresponding to the annual growth rate of employment in the non-financial corporate sector over the period 1990-2014.

**Output and Innovative Investment by Incumbent Firms** To measure innovative investment and factor payments, we use data from the Integrated Macroeconomic Accounts and Fixed Assets Tables for the US non-financial corporate sector derived from the U.S. National Income and Product Accounts (NIPA).

Since 2013, NIPA includes investments in intellectual property products. These intellectual property products include research and development, software, and artistic and literary originals. In sensitivity analysis, we consider a narrow measure of such investment corresponding to measured investment by non-financial corporations in research.
and development alone (and treat investment in software and artistic and literary originals as standard investment in physical capital).

In our model, total expenditures on innovative investments correspond to output of the research good $P_{rt}Y_{rt}$, which equals the compensation of research labor $W_{rt}L_{rt}$. We presume that what is measured in the data is the innovative investment expenditures of incumbent firms $P_{rt}(x_{ct} + x_{mt})$, and infer innovative investment expenditures of entering firms $P_{rt}x_{et}$ (since we assume that entrants are not in the non-financial corporate sector when they make these expenditures).

We measure aggregate firms’ output inclusive of the production subsidy in our model, $(1 + \tau_y)Y_t$, as Gross Value Added of the non-financial corporate sector less indirect business taxes less measured innovative investment expenditures by incumbent firms. With these adjustments, we obtain $P_{rt}(\bar{x}_c + \bar{x}_m)/(1 + \tau_y)Y_t = 0.061$ (the average of this measure for the period 1990-2014). Using the narrow measure of innovative investment expenditures by incumbent firms, this ratio is 0.030. The corresponding BGP growth rate of output of the final consumption good is $\bar{g}_Y = 0.025$ and the discount factor $\tilde{\beta} = \exp(\bar{g}_Y)/(1 + R) = 0.986$.

**Payments to Physical Capital and Profits** In the data, Gross Value Added of the non-financial corporate sector is decomposed into indirect business taxes, compensation of employees, and gross operating surplus. We measure compensation of production labor $W_{lt}L_{pt}$ in our model as compensation of employees in the non-financial corporate sector less measured innovative investment expenditures by incumbent firms.

In our model, a portion of gross operating surplus in our model is paid as rental payments to physical capital, a portion is paid as corporate profits taxes (taxes on income and wealth in the NIPA), and a portion is paid to owners of firms as after-tax variable profits less expenditures on innovative investment. To measure rental payments to physical capital, $R_kK_t$, we impute the rental rate to physical capital, $R_k = 0.103$, using the standard user cost formula implied by our model, $R_k = \frac{\bar{R}}{1 - \tau_{corp}} + d_k = 0.1027$, with a depreciation rate of physical capital $d_k = 0.055$ and a corporate profits tax $\tau_{corp} = 0.161$ calculated as described below. We measure $K_t$ by the replacement value of physical capital (“Nonfinancial assets, non-financial corporate business” minus the replacement value of intangible capital (“Nonresidential intellectual property products, non-financial corporate business, current cost basis”). We measure the depreciation rate $d_k$, as the ratio of “Consumption of fixed capital, structures, and equipment” to the replacement value of physical capital, which results in $d_k = 0.055$. We measure the corporate profits tax $\tau_c$ as the ratio of “Payments of taxes on income and wealth” in the data to the base of this tax in our model (i.e. the base of the corporate profits tax in our model is given by the sum of variable profits and physical capital income net of depreciation,
\[(1 + \tau_y) Y_t - R_k K_t - W_t L_{pt} + (R_k - d_k) K_t = (1 + \tau_y) Y_t - W_t L_{pt} - d_k K_t.\]

Following this procedure, we obtain an average share (over the period 1990 – 2014) of production labor in firms’ output (inclusive of production subsidies) of \(\frac{W_t L_{pt}}{(1 + \tau_y) Y_t} = \frac{(1 - \alpha)}{\mu} = 0.654\), a share of capital \(\frac{R_k K_t}{(1 + \tau_y) Y_t} = \frac{\alpha}{\mu} = 0.218\), and a share of variable profits in output \(\frac{1 - R_k K_t + W_t L_{pt}}{(1 + \tau_y) Y_t} = \frac{\mu - 1}{\mu} = 0.127\), so \(\alpha = 0.25\) and \(\mu = 1.146\). We assume that in the initial BGP innovative subsidies are uniform, with \(\tau_e = \tau_c = \tau_m = 0.03\), obtained from Tyson and Linden (2012) (Table 7 in that paper reports estimates of corporate R&D tax credit claims relative to R&D business spending in the U.S.). This gives us

\[\bar{d} = \frac{\bar{D}_t}{(1 + \tau_y) \bar{Y}_t} = (1 - \tau_{corp}) \left(\frac{\mu - 1}{\mu}\right) - (1 - \tau_e) \frac{\bar{P}_{rl}(\bar{x}_c + \bar{x}_m)}{(1 + \tau_y) \bar{Y}_t} = 0.047.\]

In order to remove the distortions induced by the markup and the corporate profits tax in the allocation of physical capital when calculating welfare, we set the production subsidy \(\bar{\tau}_y = \frac{\mu}{R + d_k} \left(\frac{\bar{R}}{(1 - \tau_{corp})} + d_k\right) - 1 = 0.24\). Given measures of \(\alpha\), \(\bar{g}_L\), and \(\bar{g}_Y\), we construct estimates of the BGP growth rate of total factor productivity \(\bar{g}_Z = 0.0136\). We calculate the ratio of consumption to output as

\[\bar{C} = 1 - \frac{I \bar{K}}{\bar{K} \bar{Y}} = 1 - \left(\exp(\bar{g}_Y) - (1 - d_k)\right) \frac{\alpha (1 + \tau_y)}{\mu R_k} = 0.789.\]

**Product level dynamics**: To measure the employment shares of entering firms \(\bar{s}_e\), we use annual data from the Longitudinal Business Database (LBD) in the U.S. on the dynamics of establishments and firms that own them. We make the identifying assumption that an establishment in the LBD data corresponds to an intermediate good in the model. Products in entering firms in the model correspond to establishments in the data that are new (they are active in year \(t\) but not in year \(t - 1\)) and are owned by new firms. The average value of \(\bar{s}_e\) in the period 1990-2014 is 0.027. If we assume time periods that are longer than one year, entrants represent a higher share in the total number of establishments and in employment. When we solve the model non-linearly, we calibrate other parameter values using additional information on product-level dynamics.

By equation (36), with \(\bar{d} = 0.047\), \(\exp(\bar{g}_Y) / (1 + \bar{R}) = 0.986\), and \(\bar{s}_e = 0.027\), we obtain \(\bar{v} = 1.15\). By equation (37), we obtain \(\bar{P}_{rl} \bar{x}_r / \bar{Y}_t = 0.03\), so \(\bar{t}_r = \frac{\bar{P}_{rl}(\bar{x}_r + \bar{x}_c + \bar{x}_m)}{\bar{Y}_t} = 0.093\). The fiscal cost on innovation spending, \(E / Y_t\), in the initial BGP is given by \(0.03 \times \bar{t}_r = 0.0028\).

**Business Stealing** Based on the derivation of equation (77) in Appendix B, the square
Shares in firms’ output, $Y \times (1 + \tau_y)$

<table>
<thead>
<tr>
<th>Shares in firms’ output, $Y \times (1 + \tau_y)$</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production labor compensation, $W_L$</td>
<td>0.655</td>
</tr>
<tr>
<td>Physical capital compensation, $R_K$</td>
<td>0.218</td>
</tr>
<tr>
<td>Variable profits, $\Pi = (1 + \tau_y) Y - W_L p - R_K K$</td>
<td>0.127</td>
</tr>
<tr>
<td>Innovation investments by incumbents, $P_t(x_c + x_{nm})$</td>
<td>0.061</td>
</tr>
<tr>
<td>Dividends, $(1 - \tau_{ corp}) \Pi_p (1 - \tau_c) x_c + (1 - \tau_{ nm}) x_{ nm}$</td>
<td>0.047</td>
</tr>
<tr>
<td>Innovation investments by entrants, $P_t x_e$</td>
<td>0.031</td>
</tr>
<tr>
<td>Innovation intensity, $P_t (x_c + x_{ nm} + x_e) = P_t Y_r$</td>
<td>0.093</td>
</tr>
<tr>
<td>Implied allocation of labor, $L_p / L$</td>
<td>0.880</td>
</tr>
</tbody>
</table>

Parameters

- Elasticity of substitution, $\rho$ | 4
- Markup, $\mu$ | 1.146
- Intertemporal spillovers, $\phi$ | $-1.6$ or $0.99$
- Capital depreciation rate, $d_k$ | 0.055
- Interest rate, $R$ | 0.04
- Intertemporal substitution, $\eta$ | 1
- Labor growth rate, $g_L$ | 0.007

Policies in initial BGP

<table>
<thead>
<tr>
<th>Policies in initial BGP</th>
<th>Other targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovation subsidies, $\tau_c = \tau_m = \tau_e$</td>
<td>Output growth rate, $\bar{g}_Y$</td>
</tr>
<tr>
<td>Output subsidy, $\tau_y$</td>
<td>Employment share of entrants, $\bar{s}_e$</td>
</tr>
<tr>
<td>Corporate profit tax rate, $\tau_{ corp}$</td>
<td>Entrants growth contribution, $\bar{g}_Z (G(\bar{x}_c, \bar{x}_m, 0) / \bar{g}_Z)$</td>
</tr>
</tbody>
</table>

Other model outcomes

<table>
<thead>
<tr>
<th>Other model outcomes</th>
<th>Other targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate productivity growth, $\bar{g}_Z$</td>
<td>Value of incumbents relative to $\bar{Y}(1 + \tau_y)$</td>
</tr>
<tr>
<td>Discount factor, $\bar{\beta}$</td>
<td>Term $\exp(\bar{g}_Z)^{\rho - 1} - \exp(G(\bar{x}_c, \bar{x}_m, 0))^{\rho - 1}$</td>
</tr>
<tr>
<td>Consumption/output, $\bar{C}/\bar{Y}$</td>
<td>Impact elasticity entry, $\Theta_e$</td>
</tr>
</tbody>
</table>

Table 2: Baseline parameters, targets and outcomes

The bracket in equation (34) can be written as

$$
\frac{\exp \left( \bar{g}_Z \right)^{\rho - 1} - \exp \left( G(\bar{x}_c, \bar{x}_m, 0) \right)^{\rho - 1}}{\exp \left( \bar{g}_Z \right)^{\rho - 1}} = \left( 1 - \frac{\text{av.size}_c}{\text{av.size}_e} \right) \bar{s}_e
$$

We consider two parameterizations of the extent of business stealing for entering firms. First, we set $\delta_e = 0$, so that the square bracket in equation (34) is equal to $\bar{s}_e = 0.027$. Second, we let $\delta_e > 0$, and choose $G(\bar{x}_c, \bar{x}_m, 0)$ so that $(\bar{g}_Z - G(\bar{x}_c, \bar{x}_m, 0)) / \bar{g}_Z = 0.257$, which corresponds to estimates of the portion of annual trend productivity growth due to entry in Akcigit and Kerr (2017). Given our estimate of $\bar{g}_Z = 0.014$ and $\rho = 4$, we obtain $G(\bar{x}_c, \bar{x}_m, 0) = 0.01$ and the square bracket in equation (34) is equal to 0.011. Given our measure $\frac{\text{av.size}_c}{\text{av.size}_e} = 3$ discussed below, our parameterization implies $\delta_e = 0.20$.

C.2 Additional parameters to solve non-linear transition

In the previous section we described how we assign values to the parameters determining the elasticities required to evaluate the aggregate implications of a change in innovation policies. We now discuss how we assign remaining parameter values to solve for all BGP
variables and to solve the transition dynamics of the model non-linearly and globally. We specify
\[ h(x_m) = h_1 x_m^{h_2} \]
\[ \zeta(x_c) = \zeta_0 + \zeta_1 x_c^{\zeta_2} \]

The parameters that need to be assigned are \( \{ \delta_0, \eta_e, \eta_m, h_1, h_2, \zeta_0, \zeta_1, \zeta_2 \} \). In Section C.1 we described how we choose the value of \( \delta_e \). Here we impose \( \delta_m = \delta_e \).

We now describe a procedure to calibrate all remaining parameters except for the curvature parameter \( \zeta_2 \). In our quantitative exercises, we set \( \zeta_2 \) low enough such that the \( \zeta'' / \zeta' \) is high enough (in absolute terms) and the value of \( \Theta \) defined in Propositions 6 and 7 is close to its upper bound of \( \Theta_e \) as indicated in Corollary 2.

Suppose we have data on the growth rate of the measure of products \( g_M^t = \log(M_{t+1}/M_t) \), as well as data on the fraction of products that are continuing products in incumbent firms \( f_{ct+1} \), the fraction of products that are new to incumbent firms measured as the sum of those that are new to society and stolen \( f_{mt+1} \), and the fraction of products that are produced in entering firms measured as the sum of those that are new to society and stolen \( f_{et+1} = 1 - f_{ct+1} - f_{mt+1} \). Suppose we also have data on the aggregate size of continuing products in incumbent firms \( s_{ct+1} \), the aggregate size of products that are new to incumbent firms measured as the sum of those that are new products and those that are stolen \( s_{mt+1} \), and the aggregate size of products that are new to entering firms measured as the sum of those that are new products and those that are stolen \( s_{et+1} = 1 - s_{ct+1} - s_{mt+1} \). The average size of continuing products in continuing firms, new products in incumbent firms, and new products in entering firms is denoted by \( \text{avsize}_{ct+1} = \frac{s_{ct+1}}{f_{ct+1}} \), \( \text{avsize}_{mt+1} = \frac{s_{mt+1}}{f_{mt+1}} \) and \( \text{avsize}_{et+1} = \frac{s_{et+1}}{f_{et+1}} \), respectively. Time averages of these variables are denoted with a bar.

We calibrate \( \delta_0, \eta_e, \eta_m \) and the initial BGP values of \( h(\bar{x}_m), \zeta(\bar{x}_c), \bar{x}_e \) to satisfy the following equations:

\[ h(\bar{x}_m) = \bar{f}_m \exp(\bar{g}_M) \]
\[ \bar{x}_e = \bar{f}_e \exp(\bar{g}_M) \]
\[ \zeta(\bar{x}_c) = \text{avsize}_c \frac{\exp((\rho - 1)\bar{g}_Z)}{\exp(\bar{g}_M)} \]
\[ \eta_m = \text{avsize}_m \frac{\exp((\rho - 1)\bar{g}_Z)}{\exp(\bar{g}_M)} \]
\[ \eta_e = \text{avsize}_e \frac{\exp((\rho - 1)\bar{g}_Z)}{\exp(\bar{g}_M)} \]
\[ \delta_0 = 1 - \delta_m h(\bar{x}_m) - \delta_e \bar{x}_e - F_c \exp(\bar{g}_M) \]

Given initial policy ratios, \( \left( \frac{1 - \tau_c}{1 - \tau_m} \right) \) and \( \left( \frac{1 - \tau_c}{1 - \tau_m} \right) \), we calibrate \( \zeta' (\bar{x}_c) \) and \( h'(\bar{x}_m) \) using equations (64) and (65).

In order to calibrate the parameters \( h_1, h_2, \bar{z}_1 \) and \( \bar{z}_2 \), we must know the values of \( \bar{x}_c \) and \( \bar{x}_m \). Note that our calibration procedures uses as an input a measure of \( (\bar{x}_c + \bar{x}_m) / \bar{Y}_r \) and implies a value of \( \bar{x}_c / \bar{Y}_r \), but does not pin down \( \bar{x}_c \) and \( \bar{x}_m \) separately. To determine the value of \( \bar{x}_c \) we use the following logic. The contribution of investment in acquiring products each period to firm value must be non-negative. That is, on a BGP, we must have \( \bar{v} \geq 0 \), this alternative value of incumbent firms on a BGP is given by

\[ \bar{v} = \left[ 1 - \frac{\exp(\bar{g}_y)}{1 + R} \frac{\bar{s}_c}{\bar{s}} \right]^{-1} \left[ (1 - \tau_{corp}) \left( \frac{\mu - 1}{\mu} \right) - (1 - \tau_c) \frac{\bar{P}_{rt} \bar{x}_c}{(1 + \bar{r}_y) \bar{Y}_t} \right] \]

The requirement that \( \bar{v} \leq \bar{\sigma} \) implies that the research expenditures of incumbents on improving continuing products relative to value added must lie between the bounds

\[ \frac{\bar{P}_{rt}(\bar{x}_c + \bar{x}_m)}{(1 + \bar{r}_y) \bar{Y}_t} \geq \frac{\bar{P}_{rt} \bar{x}_c}{(1 + \bar{r}_y) \bar{Y}_t} \geq \frac{1 - \exp(\bar{g}_y) \bar{s}_c}{1 - \exp(\bar{g}_y)(1 - \bar{s}_c)} \frac{\bar{P}_{rt}(\bar{x}_c + \bar{x}_m)}{(1 + \bar{r}_y) \bar{Y}_t} - \frac{\exp(\bar{g}_y) \bar{s}_m}{1 - \exp(\bar{g}_y)(1 - \bar{s}_c)} \left( 1 - \tau_{corp} \right) \left( \frac{\mu - 1}{\mu} \right) \]

In our calibration, we set \( \bar{P}_{rt} \bar{x}_c / (1 + \bar{r}_y) \bar{Y}_t \) in the middle point between the two bounds. Given values of \( \bar{x}_m, h(\bar{x}_m) \) and \( h'(\bar{x}_m) \) we can determine the values of \( h_0 \) and \( h_1 \). Given values of \( \bar{x}_c, \zeta(\bar{x}_c) \) and \( \zeta'(\bar{x}_c) \) and a value of \( 0 < \bar{z}_2 < 1 \), we can determine the values of \( \zeta_0 \) and \( \zeta_1 \).

Our model imposes the following bounds on parameters \( \delta_0, \delta_e \) and \( \delta_m \). First, \( 0 \leq \delta_0, \delta_e, \delta_m \leq 1 \). Second, the constraint that new products to society have non-negative size (\( \eta_{mn} > 0 \) and \( \eta_{en} > 0 \)), combined with the restriction above that \( \eta_{ms} \geq \zeta(\bar{x}_c) \) and \( \eta_{es} \geq \zeta(\bar{x}_c) \), implies that

\[ \delta_m < \frac{\eta_{mn}}{\zeta(\bar{x}_c)} = \frac{\text{avsize}_m}{\text{avsize}_c} \]

\[ \delta_e < \frac{\eta_{en}}{\zeta(\bar{x}_c)} = \frac{\text{avsize}_e}{\text{avsize}_c} \]

As \( \delta_m \) and \( \delta_e \) approach their upper bounds, \( \eta_{mn} \to 0, \eta_{en} \to 0, \eta_{ms} \to \zeta(\bar{x}_c), \) and \( \eta_{en} \to \)
\[ \zeta(x_c). \]

We use LBD data to measure the necessary statistics to implement this calibration procedure. Specifically, we measure \( \bar{g}_M = 0.01 \) as the annual growth rate in the number of establishments (averaged between 1990 and 2014), \( \bar{f}_e = 0.0775 \) as the fraction of establishments in the data that are new and are owned by new firms, \( \bar{f}_m = 0.0227 \) as the fraction of establishments that are new and are owned by firms that are not new, and \( \bar{f}_c = 0.9 \) as the fraction of establishments are not new. The employment share of these three categories of establishments are \( \bar{s}_e = 0.027, \bar{s}_m = 0.025, \) and \( \bar{s}_c = 0.948. \) Our results are very similar if we calibrate the model using the statistics implied in Garcia-Macia et al. (2015).

C.3 BGP Equations

The economy starts on an original BGP corresponding to policies \( \bar{\tau}_c, \bar{\tau}_m, \bar{\tau}_e \) and \( \bar{\tau}_y. \) We normalize the level of scientific progress to be \( A_{rt} = 1 \) at \( t = 0. \) This gives \( A_{rt} = \exp(t \bar{g}_{Ar}). \) We normalize the population to be \( L_t = 1 \) at \( t = 0. \) This gives \( L_t = \exp(t \bar{g}_L). \) We take as given parameters and observed growth rates of aggregate output and labor \( \bar{g}_Y \) and \( \bar{g}_L. \)

Let \( l_{pt} = L_{pt}/L_t \) and \( l_{rt} = L_{rt}/L_t. \) These variables are constant at \( \bar{l}_p \) and \( \bar{l}_r \) on the initial BGP. Let \( k_t = K_t/\exp(t \bar{g}_Y). \) This variable is constant at \( \bar{k} \) on the initial BGP. Let \( v_t = V_t/(1 + \bar{\tau}_y) Y_t \) and \( p_{rt} = P_{rt}/(1 + \bar{\tau}_y) Y_t. \) Both of these variables are constant on a BGP at \( \bar{\sigma} \) and \( \bar{\rho}_r. \) Let \( z_t = Z_t/\exp(t \bar{g}_Z) \) where we solve for the BGP value \( \bar{g}_Z \) below. Let \( \bar{z} \) denote the BGP value of this variable. Let \( y_t = Y_t/\exp(t \bar{g}_Y) \) where we calibrate the BGP value \( \bar{g}_Y. \) Let \( \bar{y} \) denote the BGP value of this variable. Let \( c_t = C_t/\exp(t \bar{g}_Y). \) Let \( \bar{c} \) denote the BGP value of this variable. The BGP equations to be solved for the value of the state variables \( Z_0 \) and \( K_0 \) are as follows.

**Growth Rates \( g_Z, g_{Ar} \)

\[
g_Z = (1 - \alpha)(\bar{g}_Y - \bar{g}_L)
\]

\[
g_{Ar} = (1 - \phi)g_Z - \bar{g}_L
\]

**Interest Rate and Rental Rate of physical capital \( \bar{R} \) and \( \bar{R}_k \)

\[
1 + \bar{R} = \frac{\exp(\gamma (\bar{g}_Y - \bar{g}_L))}{\beta}
\]

\[
\bar{R} = (1 - \tau_{cor}) (\bar{R}_k - d_k)
\]
Innovative Investment $\bar{x}_c, \bar{x}_m, \bar{x}_e$ and $\bar{Y}_r$

$$\frac{1 - \bar{x}_c \eta_e}{1 - \bar{x}_e} = (1 - \delta_0 - \delta_m h(\bar{x}_m) - \delta_e \bar{x}_e) \zeta'(\bar{x}_c)$$

$$\frac{1 - \bar{x}_m \eta_e}{1 - \bar{x}_e} = \eta_m h'(\bar{x}_m)$$

$$\bar{g}_Z = \frac{1}{\rho - 1} \log ((1 - \delta_0 - \delta_m h(\bar{x}_m) - \delta_e \bar{x}_e) \zeta(\bar{x}_c) + \eta_m h(\bar{x}_m) + \eta_e \bar{x}_e)$$

$$\bar{x}_c + \bar{x}_m + \bar{x}_e = \bar{Y}_r$$

Employment share of entering firms, value of intangible capital, price of the research good $\bar{s}_e$, $\bar{\sigma}$ and $\bar{p}_r$

$$\bar{s}_e = \frac{\eta_e \bar{x}_e}{\exp ((\rho - 1) \bar{g}_Z)}$$

$$\bar{\sigma} = \frac{\left[ (1 - \tau_{cor}) \frac{\mu}{\mu - 1} - \bar{p}_r ((1 - \bar{x}_c) \bar{x}_c + (1 - \bar{x}_m) \bar{x}_m) \right]}{1 - \exp(\bar{g}_Y) \left( 1 - \bar{s}_e \right)}$$

$$(1 - \bar{\tau}) \bar{p}_r = \eta_e \exp (\bar{g}_Y - (\rho - 1) \bar{g}_Z) \bar{\sigma}$$

Innovation intensity and allocation of labor $\bar{I}_r, \bar{I}_p, \bar{I}_r$

$$\bar{I}_r = \bar{p}_r \bar{Y}_r$$

$$\frac{\bar{I}_p}{\bar{I}_r} = \frac{1 - \alpha}{\mu} \frac{1}{\bar{I}_r}$$

$$\bar{I}_p + \bar{I}_r = 1$$

Levels of the state variables $\bar{z}, \bar{k}$

$$\bar{Y}_r = \bar{z}^{\phi - 1} \bar{I}_r$$

$$\bar{R}_k = (1 + \tau_y) \frac{\alpha \bar{y}}{\mu \bar{k}}$$

Output and consumption

Appendix 27
\[ \bar{y} = \bar{z}^a \bar{r}_p^{1-a} \]

\[ \bar{c} = \bar{y} - (\exp(\bar{g}_Y) + (1 - d_k)) \bar{k} \]

**New BGP** We consider a permanent change in innovation policies from \( \bar{\tau}_c, \bar{\tau}_m, \bar{\tau}_e \) to \( \bar{\tau}'_c, \bar{\tau}'_m, \bar{\tau}'_e \) that is unanticipated and starts in period \( t = 0 \). Thus, the economy starts in period \( t = 0 \) with the state variables \( A_{t0} = L_0 = 1 \), and \( Z_0, \bar{K}_0 \) solved for above. The economy follows a transition path to a new BGP. We can use the same procedure as above to compute the new BGP which we denote with primes. The terminal conditions we will use when we solve for the transition dynamics is that we end up at the new BGP allocation.

**C.4 Solving transition**

The two states of the model are \( z_t \) and \( k_t \). Given \( z_0, k_0 \), we wish to solve for a sequence \( \{z_{t+1}, k_{t+1}\}^T_t \), as well as the remaining intra-period variables that satisfies the Euler equations and the terminal conditions that \( z_{t}, k_{t} \) converges to the new BGP \( z', k' \).

Let \( Y_t \) denote the vector of intra-period variables:

\[ Y_t = (x_{ct}, x_{mt}, x_{et}, Y_{rt}, l_{rt}, l_{pt}, s_{rt}, p_{rt}, y_t, c_t) \]

We first show how we solve for \( Y_t \), given \( \{z_{t+1}, k_{t+1}\} \). Specifically, we solve for \( (x_{ct}, x_{mt}, x_{et}, Y_{rt}, l_{rt}, l_{pt}, i_{rt}, p_{rt}) \) given \( (z_{t}, z_{t+1}) \). We then solve for \( (y_t, c_t) \) given \( (z_{t}, z_{t+1}, l_{pt}) \) from the previous step, and \( (k_t, k_{t+1}) \).

**Allocation of innovative investment** \( x_{ct}, x_{mt}, x_{et}, Y_{rt} \) (assuming that the allocation is interior):

\[ \log z_{t+1} - \log z_t + \bar{g}_z = \frac{1}{\rho - 1} \log \left( (1 - \delta_0 - \delta_m h(x_{mt}) - \delta_e x_{et}) \zeta(x_{ct}) + \eta_m h(x_{mt}) + \eta_e x_{et} \right) \]

\[ \frac{1 - \bar{\tau}_e}{1 - \bar{\tau}_e} \eta_e = \left( 1 - \delta_0 - \delta_m h(x_{mt}) - \delta_e x_{et} \right) \zeta'(x_{ct}) \]

\[ \frac{1 - \bar{\tau}_m}{1 - \bar{\tau}_e} \eta_e = \eta_m h'(x_{mt}) \]
\[ x_{ct} + x_{mt} + x_{ct} = Y_{rt} \]  

**Allocation of labor \( l_{rt}, l_{pt} \)**

\[ Y_{rt} = z_i^{\phi-1} l_{rt} \] (84)

\[ l_{pt} + l_{rt} = 1 \] (85)

**Price of the research and innovation intensity \( i_{rt}, p_{rt} \)**

\[ \frac{l_{pt}}{l_{rt}} = \frac{1 - \alpha}{\mu} \frac{1}{i_{rt}} \] (86)

\[ i_{rt} = p_{rt} Y_{rt} \] (87)

**Output and consumption \( y_t, c_t \)**

\[ y_t = z_t k_t^{\alpha} l_{pt}^{1-\alpha} \] (88)

\[ c_t = y_t + (1 - d_k) k_t - \exp(\bar{g}_Y) k_{t+1} \] (89)

We now consider the Euler equations that must be satisfied.

**Standard Physical Capital Euler Equation**

\[ R_t = (1 - \tau_{cor}) \left( (1 + \tau_y) \frac{\alpha}{\mu} \frac{y_{t+1}}{k_{t+1}} - d_k \right) \] (90)

\[ 1 = (1 + R_t) \tilde{\beta} \exp(-\bar{g}_Y) \left( \frac{c_{t+1}}{c_t} \right)^{-\eta} \] (91)

**Value Function and Zero Profit at Entry Condition**

\[ v_t = (1 - \tau_{cor}) \frac{\mu - 1}{\mu} - p_{rt} ((1 - \tau_e)x_{ct} + (1 - \tau_m)x_{mt}) + \]

\[ \exp(\bar{g}_Y - (\rho - 1)\bar{g}_Z) \frac{1}{1 + R_t} v_{t+1} \left( \frac{y_{t+1}}{y_t} \left( \frac{z_t}{z_{t+1}} \right)^{\theta - 1} \right) \right] \]

\[ \left[ (1 - \delta_0 - \delta_m h(x_{mt}) - \delta_e x_{ct}) \zeta(x_{ct}) + \eta_m h(x_{mi}) \right] \]

and

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\[(1 - \tau_e)p_{rt} = \eta_t \exp(\bar{g}_Y - (\rho - 1)\bar{g}_Z) \frac{v_{t+1}}{1 + R_t} \left( \frac{y_{t+1}}{y_t} \right) \left( \frac{z_t}{z_{t+1}} \right)^{\rho - 1} \] (93)

Let

\[X_t = (z_t, k_t, v_{t-1})\]
denote the vector of state variables extended with the lagged value of \(v_t\). If we specify the triple \(X_t, X_{t+1}, X_{t+2}\), we can solve for \(Y_t\) and \(Y_{t+1}\), and we calculate the Euler equations above. We can then solve for the path of \(\{X_t, Y_t\}\) using standard linear or nonlinear methods.

**Solving transition taking as given a path of innovation intensities or research labor**

Given \(z_0, k_0\), consider a given path of policy ratios \(\frac{1 - \tau_{ct}}{1 - \tau_{et}}, \frac{1 - \tau_{mt}}{1 - \tau_{et}}\), as well as research labor \(\{l_{rt}\}\) or the innovation intensity of the economy \(\{i_{rt}\}\) (recall that equation (86) allows us to calculate \(i_{rt}\) given \(l_{rt}\) or vice versa). We can solve for \((z_{t+1}, x_{ct}, x_{mt}, x_{et}, Y_{rt}, l_{pt}, p_{rt})\) using equations (81)-(87), given time-varying policy ratios \(\frac{1 - \tau_{ct}}{1 - \tau_{et}}\) and \(\frac{1 - \tau_{mt}}{1 - \tau_{et}}\). Given the path of \(\{z_t\}\), we can solve for \(\{y_t, c_t, k_{t+1}\}\) using equations (88)-(89) and the Euler equations for physical capital (90)-(91). Finally, we can solve for a time-varying path of \(\{\tau_{ct}, \tau_{mt}\}\) using the Euler equations (92)-(93). Finally, we can calculate \(\{\tau_{ct}, \tau_{mt}\}\).

**C.5 Figures**

Figure 1 displays the non-linear transition dynamics of aggregate productivity and output 100 years after the policy change that increases research labor permanently by 10%, for each of our 4 specifications. Figure 2 displays the transition dynamics of aggregate productivity and output zooming into the initial 20 years after the policy change. Figure 3 displays the 20-year transition dynamics of fiscal expenditures \(E/Y\) and the innovation subsidy rate \(\tau_{et}\) that produces the 10% permanent increase in research labor. Figure 4 compares the path of aggregate productivity and output calculated using the linear solution method (as in Table (1)) and the non-linear solution method.

Our results in Section 7 suggest that it would be hard to verify whether innovation policies yield large output and welfare gains using medium term data on the response of aggregates to changes in innovation policies. We illustrate this point in Figure 5. In that figure we show results obtained from simulating the response of aggregates in our model to our baseline increase in innovation subsidies in an extended version of our model with Hicks neutral AR1 productivity shocks with a persistence of 0.9 and an annual standard deviation of 1.8. We introduce these shocks as a proxy for business cycle shocks around Appendix 30
the BGP. We show histograms generated from 3000 simulations of the model for the first 20 years of the transition. The units on the horizontal axis show the log of the ratio of detrended output (in the upper panel) and productivity (in the lower panel) at the end of the 20th year of transition to initial output or productivity. The vertical axis shows the frequency of the corresponding outcome for output or productivity. The red bars show results for the model with low intertemporal knowledge spillovers and the blue bars show the results with high spillovers. We can observe in each panel that the distribution represented by the blue bars is slightly to the right of that represented by the red bars. But it is also clear in each panel that, using either output or productivity, that it would be very hard to distinguish the degree of intertemporal knowledge spillovers (and, hence, the long term effects from this innovation subsidy) in aggregate time series data even if we had the benefit of a true policy experiment.

Figure 1: 100-year transition dynamics to a 10 percent permanent increase in research labor, Nonlinear Solution
Figure 2: 20-year transition dynamics to a 10 percent permanent increase in research labor, Nonlinear Solution
Figure 3: Fiscal expenditures and innovation subsidy rate, 20-year transition dynamics to a 10 percent permanent increase in research labor, Nonlinear Solution
Figure 4: 100-year transition dynamics to a 10 percent permanent increase in research labor, Nonlinear versus linear solution
Figure 5: Histogram 20-year Increase in Aggregate Output and Productivity to a Permanent 10% Increase in Research Labor, Including Productivity Shocks

D Model extensions

D.1 Occupation choice

Suppose that workers each period draw a productivity $a$ to work in the research sector, where $a$ is drawn from a cdf $F(a)$ that is Pareto with minimum 1 and slope coefficient $\chi > 1$. There are two wages, $W_{pt}$ and $W_{rt}$. For the marginal agent,

$$\bar{a}_t W_{rt} = W_{pt}$$

Given that the minimum value of $a$ is 1, any interior equilibrium with positive production requires $W_{rt} \leq W_{pt}$. The aggregate supplies of production and research labor (relative to
the total labor force, which grows exogenously) are

\[ l_{pt} = F(\bar{a}_t) = 1 - a_t^{-\chi} \]

\[ l_{rt} = \int_{\bar{a}_t}^{\infty} a f(a) \, dx = \frac{\chi}{\chi - 1} \bar{a}_t^{1-\chi}. \]

The ratio of labor \( l_{rt} / l_{pt} \) and wages \( W_{rt} / W_{pt} \) are determined by

\[ \frac{W_{rl}l_{rt}}{W_{pl}l_{pt}} = \frac{\mu}{(1 - \alpha)} i_{rt} \]

\[ \frac{l_{rt}}{l_{pt}} = \frac{\chi}{\chi - 1} \left( \frac{W_{pt}}{W_{rt}} \right)^{1-\chi} \left( 1 - \left( \frac{W_{pt}}{W_{rt}} \right)^{-\chi} \right). \]

Note that as \( \chi \) goes to infinity, \( W_{rt} / W_{pt} \) must converge to 1 in order for \( l_{rt} / l_{pt} \) to be finite. The elasticity of research labor with respect to the innovation intensity of the economy is

\[ (\log l'_{rt} - \log l_{rt}) = \frac{(\chi - 1)}{(\chi - 1) \left( 1 + \frac{W_{l}}{W_{l}} \right) + 1} (\log i'_{rt} - \log i_{rt}) \]

When \( \chi \) converges to 1 (high worker heterogeneity), the elasticity of \( l_{rt} \) with respect to \( i_{rt} \) converges to 0. When \( \chi \) converges to infinity (no worker heterogeneity), this elasticity converges to \( l_p \), as in our baseline model.

**D.2 Goods and Labor used as inputs in research**

We consider an extension in which research production uses both labor and consumption good, as in the lab-equipment model of Rivera-Batiz and Romer (1991), and discuss the central changes to our analytic results. Specifically, the production of the research good is given by

\[ Y_{rt} = A_{rt} Z_t^{\phi-1} L_t^\lambda \chi_t^{1-\lambda}, \]

and the resource constraint of the final consumption good is

\[ C_t + K_{t+1} - (1 - d_k) K_t + X_t = Y_t. \]
Given this production technology, the BGP growth rate of aggregate productivity is given by  
\[ \bar{g}_Z = \frac{\bar{g}_\zeta + \bar{g}_L}{1 - \bar{\phi}} \], where  \( \bar{\phi} = \phi + \frac{1 - \lambda}{1 - \alpha} \). The condition for semi-endogenous growth is  \( \bar{\phi} < 1 \) (equality for endogenous growth).

Revenues from the production of the research good are divided as follows

\[ W_t L_{rt} = \lambda P_{rt} Y_{rt}, \quad \text{and} \quad X_t = (1 - \lambda) P_{rt} Y_{rt}. \]

The analogous to equation (14), relating the allocation of labor between production and research to the innovation intensity, is

\[ l_{rt} = \frac{i_{rt}}{i_{rt} + \frac{(1 - \alpha)}{\mu \lambda}} \quad \text{and} \quad l_{pt} = 1 - l_{rt} \quad (94) \]

where  \( i_{rt} \equiv P_{rt} Y_{rt} / \left( (1 + \tau_y) Y_t \right) \). Our analytical results need to be modified for two reasons. First, for a given share of production labor in output  \( (1 - \alpha) / \mu \), the elasticity of research labor  \( l_{rt} \) with respect to the innovation intensity of the economy  \( i_{rt} \) is decreasing in  \( \lambda \). A higher share of goods in production of the research good (lower  \( \lambda \)) increases the sensitivity of  \( l_{rt} \) with respect to  \( i_{rt} \).

Second, the elasticity of research output  \( Y_{rt} \) with respect to a change in research labor is given by

\[ \log Y'_{rt} - \log Y_r = (\log l'_{rt} - \log L_r) - (1 - \bar{\phi}) (\log Z'_t - \log Z_t) - \frac{(1 - \lambda) \alpha}{1 - \alpha} (\log R'_{kt} - \log R_k) \]

The role that the term  \( \phi \) played in shaping the dynamics of aggregate productivity in the baseline economy (see Propositions 1 and 2) is now played by  \( \bar{\phi} \). A lower value of  \( \lambda \) increases  \( \bar{\phi} \) and the associated long term productivity gains from a given increase in research labor. The third term in the right hand side reflects the change in research output  \( Y_{rt} \) that result when  \( \lambda < 1 \) from changes in the capital/output ratio.

For given changes in research output, the determination of innovation investments by firms does not depend on the parameter  \( \lambda \).