Pareto Optimal Pro-cyclical Research and Development

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Abstract

We develop a perfectly competitive endogenous growth model in which R&D is the engine of growth. Our model generates pro-cyclical R&D investment and labor input as a pareto optimal response to technology shocks to the consumption and equipment good sectors. The model also reproduces a variety of facts from the U.S. economy. Growth in R&D capital accounts for 75 percent of the growth rate of GNP and the decline in the relative price of equipment investment. Investment in each sector is pro-cyclical. Our results suggest that equipment shocks may be less important than the previous literature has found. After accounting for the endogenous response of R&D, equipment sector shocks only account for a small fraction of the variance in the growth rate of GNP.

Keywords: Pareto Optimal, Growth, Fluctuations, R&D

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1 Introduction

This paper considers the cyclical pattern of research and development (R&D) in a model with perfectly competitive endogenous growth. We are interested in understanding the extent to which pro-cyclical R&D is a puzzle for a Pareto Optimal endogenous growth model that can be decentralized with perfectly competitive markets.

Barlevy (2007) argues that a Pareto optimal plan is associated with counter-cyclical R&D investment. He supposes that R&D investment is labor intensive, and the productivity of R&D investment is a-cyclical. Then the fact that labor productivity in goods production is pro-cyclical implies that R&D production should optimally be concentrated in periods when labor productivity in goods production is low. The fact that R&D is pro-cyclical in U.S. data then indicates the presence of market imperfections. A government policy that taxes R&D when labor productivity is high and subsidies R&D when labor productivity is low could help correct this imperfection.

We propose an endogenous growth model with an R&D sector and two other sectors: a consumption sector that produces consumption goods and structures and a sector that produces equipment. Previous work by Gordon (1990), Greenwood, Hercowitz and Krusell (1997) and Cummins and Violante (2002) has documented a steady decline in the relative price of equipment in U.S. data. One explanation for this trend is that the benefits of R&D investment are concentrated in equipment. Our model posits this channel and produces a declining relative price of equipment as an endogenous response to R&D investment.

The model we consider falls in the class of perfectly competitive endogenous growth models considered by e.g. Boldrin and Levine (2008) and Jones and Manuelli (2005). It also exhibits scale effects. The growth rate of the economy depends on both the level of the technology in the R&D sector and the number of researchers.

Business cycles in our model arise due to variations in the state of technology in the consumption and equipment sectors. Greenwood, Hercowitz and Krusell (2000) and Fisher (2006) find that shocks to equipment/investment are important sources of business cycle variation in the U.S. We allow for technology shocks to both the consumption sector and the equipment sector.

Allowing for multiple sectors creates another issue. In U.S. data R&D investment, equipment investment and structures investment are all positively correlated with GNP. We would like our model to reproduce these facts. Christiano and Fisher (2003) generate positive co-movements across consumption and investment sectors using a specification that posits adjustment costs on investment and a positive correlation among shocks to both sectors. We also find the adjustment costs are important in generating pro-cyclical R&D, equipment and structures investment. However, we assume that the shocks to technology in each sector are uncorrelated with each other.

We use two different methods to document the cyclical properties of R&D investment and labor input in our model. First, we report impulse response functions to each shock. Our perfectly competitive model with adjustment costs on equipment and structures investment produces a pro-cyclical impact response of R&D investment expressed in consumption units and researcher input in R&D production to either shock.

Second, we conduct simulations to see whether the model can reproduce the magnitudes of the correlations that we observe in U.S. data. When we allow for adjustment costs to equipment and structures the model reproduces the small weak positive correlation of labor input in R&D with GNP seen in U.S. data. The model also reproduces the stronger correlation of R&D investment with GNP. The fit of the model in other dimensions is also generally good.

Comin and Gertler (2006) document strong co-movements at medium term frequencies in U.S. data and find that these co-movements are associated with variation in U.S. R&D expenditures. Braun, Okada and Sudou (2006) find that medium cycle variations in U.S. R&D are also strongly associated with medium cycle variations in Japanese TFP and economic activity. Given that the accumulation of R&D capital is the engine of growth in our model, it is interesting to know how well the model does in reproducing medium cycle variations in U.S. data. Our model produces medium cycle variations that are in good accord with U.S. data.

Our model is also consistent with growth observations. Greenwood, Hercowitz and Krusell (1997) have previously argued that it is difficult to reproduce the trend in the relative price of equipment and output growth using endogenous growth models. Our model reproduces 75% of the growth rate of GNP and 75% of the average measured decline in the relative price of equipment. This leaves a remainder of 25% to be accounted for by other factors such as free spillover effects as in Klenow and Rodriquez-Claire (2005).

Finally our model also has some new implications for the contribution of equipment sector shocks to the business cycle. Greenwood, Hercowitz and Krusell (2000) find that technology shocks to the equipment sector account for as much as 38 percent of the variation in output over the business cycle. Fisher (2006) finds that these same shocks can account for as much as 80 percent of the variance in output over the business cycle. In our model technology shocks to the equipment sector account for less than 2 percent of the variance in the growth rate of output.

The remainder of the paper is organized as follows. Section 2 describes the model and the growth properties of our mode. Section 3 describes how we parameterize the model. Section 4 reports impulse responses. Section 5 reports simulation results and Section 6 contains our concluding remarks.

2 Model

We consider a homogenous agent economy with three productive sectors and perfectly competitive innovation as in Boldrin and Levine (2008) and scale effects as in Jones and Manuelli (2005). We want a perfectly competitive endogenous growth model because we are interested in understanding whether pro-cyclical R&D might be a Pareto Optimal response to technology shocks.

We are interested in an endogenous growth model with scale effects because we want a specification in which taxes and/or subsidies to R&D investment affect economic growth. Households value consumption, c_t, using a utility function that exhibits endogenous habit persistence:

$$U = \sum_{t=0}^{\infty} \beta^t \frac{(c_t - bc_{t-1})^{1-\sigma}}{1-\sigma} \tag{1}$$

where $0 \leq b \leq 1$ governs the strength of habit persistence. The consumption good is produced using equipment, h_t^c, structures, k_t^c, and non-research labor input, $L_{2,t}^c$ using a constant returns to scale Cobb-Douglas production function:

$$y_t^c = A_t (k_t^c)^{\theta_k} (h_t^c)^{\theta_h} (L_{2,t}^c)^{1-\theta_k-\theta_h}. \tag{2}$$

Output of the consumption sector, y_t^c, is either invested to produce new structures ($x_{k,t}$) or consumed by households:

$$y_t^c = c_t + x_{k,t}. \tag{3}$$

Investment in new structures, k_t, is subject to adjustment costs:

$$k_t = (1-\delta_k)k_{t-1} + x_{k,t} - \frac{\phi_k}{2}\left(\frac{x_{k,t}}{x_{k,t-1}} - \gamma_k\right)^2 x_{k,t} \tag{4}$$

We will see below that adjustment costs on structures play an important role in generating comovements among sectors.

Equipment and structures are inputs to production in the consumption sector and the equipment sector:

$$h_{t-1} = h_t^c + h_t^h \tag{5}$$

$$k_{t-1} = k_t^c + k_t^h. \tag{6}$$

Equipment investment goods, x_{ht}, are produced using a constant returns to scale Cobb-Douglas production technology that combines equipment, structures, R&D capital, research labor and non-research labor:

$$x_{h,t} = A_{h,t}(L_{1,t}^h H_{t-1})^{\alpha_H} (k_t^h)^{\alpha_k} (h_t^h)^{\alpha_h} (L_{2,t}^h)^{1-\alpha_k-\alpha_h-\alpha_H}. \tag{7}$$

Jones and Manuelli (2005) propose a similar production technology. It has the property that R&D capital, H_{t-1}, is attached to research workers, $L_{1,t}$. We also allow for adjustment costs to investment in new equipment:

$$h_t = (1-\delta_h)h_{t-1} + x_{h,t} - \frac{\phi_h}{2}\left(\frac{x_{h,t}}{x_{h,t-1}} - \gamma_h\right)^2 x_{h,t}. \tag{8}$$

Adjustment costs on equipment investment generate pro-cyclical labor input in the R&D investment sector. R&D investment, $x_{H,t}$, is produced by research workers:

$$x_{H,t} = A_{H,t} H_{t-1} L_{1,t}^H. \tag{9}$$

Our assumption that research workers are the only input in the R&D investment sector is designed to emphasize the notion that the creation of new business ideas is labor intensive and uses a scarce pool of research labor input. In fact, we assume that the pool of research labor and non-research labor is fixed:

$$L_1 = L_{1,t}^H + L_{1,t}^h \tag{10}$$

$$L_2 = L_{2,t}^h + L_{2,t}^c. \tag{11}$$

These assumptions imply that the scale of productivity in the R&D investment sector, $A_{H,t}$, and the number of researchers, L_1, affect the long-run growth rate of the economy. Government taxes and/or subsidies to R&D investment also affect the growth rate of the economy. An alternative approach would be to allow for population growth in a semi-endogenous growth model as in Jones (1995). In that model tax policy on R&D has no implications for the long-run growth rate of the economy. We are interested in allowing for the possibility that tax policy on R&D affects growth rates. That is why we use this specification.

We also allow for adjustment costs to investment in new R&D:

$$H_t = H_{t-1} + x_{H,t} - \frac{\phi_H}{2}\left(\frac{x_{H,t}}{x_{H,t-1}} - \gamma_H\right)^2 x_{H,t}. \tag{12}$$

Finally, we will allow for shocks to technology in equipment production and consumption production:

$$\ln(A_t) = (1-\rho)\ln(\bar{A}) + \rho\ln(A_{t-1}) + \epsilon_t \tag{13}$$

$$\ln(A_{h,t}) = (1-\rho_h)\ln(\bar{A}_h) + \rho_h\ln(A_{h,t-1}) + \epsilon_{h,t}. \tag{14}$$

This completes the description of our economy. This is an example of a convex economy with endogenous growth as described in Jones and Manuelli (1990) and the first and second welfare theorems apply.

The equilibrium conditions and derivation of the balanced growth path for our economy are described in a technical appendix that is available upon request to either of the authors. Here we summarize the most important properties of the balanced growth path.

Along the balanced growth path the growth rate of the stock of structures is given by:

$$\gamma_k = \left[\beta(1 + A_H L_1)\right]^{\frac{1}{\sigma+\omega_H-1}} \tag{15}$$

where,

$$\omega_H \equiv \frac{1-\theta_k}{\theta_h}\frac{1-\alpha_h}{\alpha_H} - \frac{\alpha_k}{\alpha_H} \geq 1. \tag{16}$$

Equation (15) illustrates several important properties of our model. First, the model exhibits endogenous growth when $\omega_H > 1$. Second, our economy has scale effects. Both the level of total factor productivity in the R&D sector and the economy wide endowment of research workers affect the growth rate of the economy. Third, the growth rate of the economy is independent of the level of the technology in the consumption and equipment investment sectors.

The growth rate of the relative price of equipment along the balanced growth path is given by

$$\gamma_{x_h} = \gamma_k^{1-\omega_h} \leq 1, \tag{17}$$

where

$$\omega_h = \frac{1-\theta_k}{\theta_h} \geq 1 \tag{18}$$

Thus the model generates "investment-specific technical change."

3 Calibration

We calibrated our model parameters using three types of data facts: shares of output and other stationary ratios, average growth rates and second moments. Some of the model parameters are well identified from the first moment properties of the data. This includes the production function share parameters for goods and equipment production. In our economy the average growth rate of the economy is also affected by the production technology parameters as well as the relative risk aversion coefficient and preference discount factor. The adjustment cost parameters and the shock variances are identified using second moments.

Table 1 lists the structure parameters and the data facts used to identify them. We consider two parameterizations of the model. The first parameterization sets adjustment costs on equipment investment to zero and the other allows for adjustment costs on equipment investment. Many of the parameters are the same across these two parameterizations so we report them first. Our calibrated value of A_H implies that the return on R&D is 9.2% per annum. We set the shares on consumption goods production so that the capital share is 0.36 and labor's share is 0.64. Greenwood, Hercowitz and Krusell (1997) assume that the share of structures is 1/2 as large as equipment's share. We make the same assumption here. We also imposed the restriction that structures are half the share of equipment in equipment goods production. We set $\beta = 0.992$ on a priori grounds. This is a bit lower than the value of 0.99999 used in e.g. Boldrin, Christiano and Fisher (2001). The two depreciation rates are chosen to reproduce the average depreciation rates of equipment and structures in U.S. data. We set the endowment of researchers to 1 and the endowment of non-researchers is set to 100. Thus researchers make up about 1 percent of the working population. The auto-regressive coefficients ρ and ρ_h are both set to 0.95.

Our first moment data facts are the share of equipment in output, the share of consumption in output, and the growth rate of output. We tried to match all three facts jointly using the parameters: α_k, α_H, and σ but we found that it is impossible to do this using our model. Appendix A contains a discussion of this issue. So we decided to calibrate the model to reproduce the two share variables and then try to come as close as possible to reproducing output growth. We chose this strategy because we believe that it is too much to assign all growth to endogenous growth in the model. Previous research by Klenow and Rodriguez-Claire (2005) have found that it is difficult to account for cross-sectional levels differences without appealing to costless spillovers of ideas from other countries. From the perspective of our model costless spillovers can be interpreted as exogenous growth.

Turning next to second moments. A variety of papers including, Braun and Evans (1998), Christiano and Fisher (2003) and Christiano, Eichenbaum and Evans (2005) have found that allowing for habit persistence in consumption improves the seasonal and business cycle properties of real and nominal sticky price representative agent economies. We set b to 0.4 which is somewhat lower than the value used in these other papers. This choice helps us to reproduce consumption volatility in U.S. data. It also acts to increase the autocorrelation of consumption growth.

We set the adjustment cost on structures investment to reproduce the relative volatility of structures investment to equipment investment in U.S. data. We found that the setting of the adjustment cost on equipment is important in generating a pro-cyclical response of researcher labor input in the R&D sector. For this reason we will report results for two values of this parameter. The value of the adjustment cost on R&D investment is less important for our conclusions so we set it to 0.7. Finally, we set the variance of the shocks to equipment and consumption goods to reproduce the volatility of equipment investment in consumption units and the volatility of output growth.

4 Pro-cyclical R&D

Barlevy (2007) argues that it is a challenge to generate pro-cyclical R&D as a Pareto optimal response in a model where R&D is labor intensive, labor productivity is pro-cyclical and the productivity of R&D is a-cyclical. We now turn to describe situations in which our model produces pro-cyclical R&D. Before documenting the cyclicality of R&D in the model we wish to emphasize that our model satisfies each of Barlevy's conditions. Our model is Pareto Optimal by construction. R&D is research labor intensive- it is the only input in R&D production. Our production functions have the property that an improvement in technology in either the consumption or equipment sector raises labor's productivity in the same sector. Finally, productivity of the R&D sector is constant by assumption. There are two different definitions of pro-cyclical R&D. The first is based on outputs. We will define pro-cyclical R&D to mean that the value of R&D in consumption units moves in the same direction as GNP also expressed in consumption units when technology is perturbed up in a particular sector. A second definition of pro-cyclical R&D focuses on inputs. We will also investigate whether labor input in the R&D sector moves in the same direction as GNP in response to an improvement in technology in each sector. In this section we use impulse response functions to assess the question of pro-cyclical R&D and focus on the impact response to each shock. We believe that this analysis provides useful insights into the economic mechanisms that are operating here. Readers who are interested in the punchline may want to skip this section and proceed directly to the Simulation Results section.

Figure 1 reports impulse responses to a positive innovation in technology in the consumption good sector for the parameterization with no adjustment costs on equipment investment. This figure shows the response of output in each sector, output in units of consumption goods for the equipment and R&D sectors, GNP, the relative price of equipment and R&D, research labor input in R&D production and non-research labor input in equipment production. All variables except labor inputs are expressed in growth rates. This shock generates a pro-cyclical response of R&D investment expressed in consumption units. Both GNP and R&D investment in consumption units increase on impact in response to an improvement in the consumption good technology. Production in the R&D sector though is falling. Since researcher labor input is the only factor in R&D investment production it has to fall too. The reason for these responses is that equipment production is more attractive. Equipment production is increasing and attracting all factors including both types of labor input, equipment and structures. Even though factors are flowing away from the consumption goods sector output of that sector is higher due to the improvement in technology. This acts to increase both consumption and investment in structures. To summarize this shock generates a pro-cyclical response of outputs and investment in all three sectors in consumption units but has the property that researcher labor input in R&D is countercyclical.

Adjustment costs on structures investment are important in generating comovements across outputs (expressed in consumption units). If the adjustment costs on structures are set to zero resources flow out of the equipment sector and into to the consumption goods and R&D sectors instead. Both R&D output and input are pro-cyclical. However, the investment sector is depressed.

Figure 2 reports impulse responses to an improvement in the technology for producing equipment investment. According to our definitions this shock has the property that R&D investment and R&D labor are both pro-cyclical. However, it does so by inducing a negative response of both consumption good production and R&D production. Equipment production increases and attracts factors but this acts to depress both consumption goods production and R&D investment in consumption units.

Next we turn to consider impulse responses when there are adjustment costs on equipment investment. Responses to a consumption sector shock are reported in Figure 3. A comparison of Figure 1 with Figure 3 reveals some important differences. Now R&D investment production and researcher input allocated to R&D production are both higher. In other respects the results are similar to before. Output in the equipment sector continues to rise and attracts all factors other than researcher labor input.

A comparison of the responses to investment productivity shocks as reported in Figures 2 and 4 also reveals some interesting distinctions. Now the response of consumption good output and R&D output are both positive. In order for this to happen resources now flow out of the investment sector. On the one hand, production of equipment is higher but the relative price decline of equipment investment is so large that equipment investment falls in consumption units.

To summarize, the impulse responses indicate that it is in principal possible to generate a pro-cyclical response of both R&D investment and researcher input in R&D production in response to either shock. However, it is still an open question as to whether the pattern of pro-cyclical R&D produced by our model is consistent with U.S. data when both shock are operating at the same time. Moreover, the impulse response functions suggest that when both shocks are operating it may be difficult to generate comovements across all three sectors. We now report simulation results that are designed to address these two issues.

5 Simulation results

In this section we document the (unconditional) first and second moment properties of our model. Our model has a rich dynamic structure that offers implications for average growth rates of output and relative prices, and also comovements among macroeconomic variables at business cycle and medium term cycle frequencies.

Table 2 reports first moment properties of our model and U.S. data. In order to compare NIPA account data with our model we adjusted the NIPA account data to reflect R&D investment. Our adjustments use the satellite accounts which are an effort by the BEA to measure R&D investment in a way consistent with the measurement of other types of investment. Table 2 shows the trade-off between growth rates and output shares that we described in the calibration section. In our endogenous growth model the same parameters that pin down consumption's share of output also determine the growth rate of output and the growth rate of the relative price of equipment. In Appendix A we explain why it is impossible for our model to reproduce all three data facts simultaneously and show the important role played by the relative risk aversion coefficient (σ). Here we simply document the nature of this trade-off. Our baseline parameterization which sets $\sigma = 3$ reproduces consumptions and equipment's share of output. Using this calibration the model reproduces about 75% of the measured growth rate of GNP and (the decline in) the relative price of equipment. If instead we assume that preferences are logarithmic ($\sigma = 1$) consumptions share of output falls to 0.57 but the model now reproduces the growth rate of GNP and the growth rate of the relative price of equipment. As described above it is our view that there are likely other (exogenous) factors that contribute to the growth rate of GNP. Our estimates imply that the overall contribution of these other factors is about 25%.

The model also produces a rapid decline in the relative price of R&D. In our model the decline in the price of R&D will always be more rapid than the relative price decline in equipment. The reason for this is that equipment production uses structures as an input but R&D production doesn't use structures as an input. In the satellite accounts constructed BEA, on the other hand, the relative price of R&D falls at a slower rate than equipment.

Finally, it should be noted that our baseline parameterization understates the share of structures and thereby overstates the share of R&D as compared to the satellite accounts data. In our data the share of R&D investment in output is 0.027 whereas in the model its value is 0.094. Inasmuchas the BEA measurement of R&D does not seek to directly measure human capital we are not too concerned about this gap between our theory and U.S. data.

Table 3 reports assorted second moments for the model and U.S. data. The model results are based on the parameterization which sets adjustment costs on equipment to zero. Both the model and U.S. data have been filtered using the Christiano and Fitzgerald (2003) bandpass filter. We report results for two settings of the filter. The results reported under the heading Business Cycle Filter have been filtered to focus on cycles with duration of 8 years or less. The results reported under the heading Medium Cycle Filter have been filtered to retain all cycles of duration 50 years or less. Comin and Gertler (2006) argue that there are important medium term comovements in U.S. data and that these comovements are associated with variations in R&D. They use a model with imperfectly competitive R&D to account for these comovements. Braun, Okada and Sudou (2006) also find strong medium term comovements between U.S. R&D and Japanese TFP and Japanese economic activity. R&D is the engine of growth in our model and we are interested in understanding the ability of our model to account for both types of comovements.

The specification with no adjustment costs on equipment successfully reproduces a positive correlation of output with R&D investment but fails to produce pro-cyclical research input in R&D. Looking first at R&D investment observe that the magnitude of the correlation is about right. Using the NIPA satellite account data the correlation of U.S. R&D investment with GNP is 0.61. Our model predicts a correlation of 0.61. Barlevy reports that the correlation of researcher input in R&D with GDP is 0.1 using a growth rate filter. Under our business cycle filter this correlation is -0.39. These same conclusions arise when we use the medium term cycle filter. Our analysis of impulse response functions found that an improvement in the technology for producing consumption goods lowers time allocated by researchers to R&D activities when adjustment costs on equipment investment are zero. Quantitatively consumption sector shocks are dominant here and the result is that researcher labor input in the R&D sector is counter-cyclical.

In other respects this parameterization of the model is in good accord with the data. The model successfully reproduces comovements of consumption with GNP, structures, total investment and equipment investment with GNP. Structures investment's correlation with output is a bit low: 0.38 for the model as compared to 0.69 in U.S. data. Other implications of the model are also good. For instance, the model delivers about the same amount of consumption smoothing that we see in U.S. data at business cycle frequencies.

These conclusions are robust to the choice of filter. Under the medium cycle filter the correlation of R&D investment with output is 0.72 as compared to 0.15 in our data. For purposes of comparison Comin and Gertler (2006) use data from the NSF on R&D expenditures. The correlation of R&D with output using their data is 0.3. Comovements of structures investment, equipment investment and consumption are also positive under the medium cycle filter and the magnitude of the correlations is about the same size as in U.S. data. The implications of the model for medium cycle volatilities is also in good accord with the data. The volatilities of investment, equipment investment and R&D investment are all of about the same magnitude as in U.S. data. The only exception is structures investment which is much more volatile in the model than in U.S. data. This is somewhat surprising given that we impose large adjustment costs on investment in structures. In terms of correlations the main gap between the model and data is research labor devoted to R&D. In the model this correlation is slightly negative (-0.03).

Previous research by Greenwood, Hercowitz and Krusell (2000) and Fisher (2006) has emphasized the important role of equipment/investment technology shocks in understanding the U.S. business cycle. Fisher (2006), for instance, finds that equipment sector technology shocks account for as much as 80 percent of business cycle variation in U.S. output.

In our specification with no adjustment costs on equipment these shocks are not an important source of variability in GNP. This conclusion can be seen by considering Table 4 which reports variance decompositions using a growth rate filter. Less than 1 percent of the variance of output is due to equipment sector productivity shocks. Equipment sector technology shocks are important in producing variation in equipment investment. They account for about half of its variance. However, equipment sector productivity shocks only account for 8 percent of the variability of equipment investment expressed in consumption units. The effects of higher productivity on equipment production are offset by lower equipment goods prices. In addition, the consumption value of R&D investment falls. This is why these shocks account for such a small fraction of the variance in output.

We saw in Section 3 that allowing for adjustment costs on equipment investment induces a positive impact response in both GNP and researcher input in the R&D sector under either type of shock. We now turn to see whether such a parameterization can produce a positive correlation of R&D researcher input with GNP. Results for this parameterization are reported in Tables 5 and 6. Looking first at Table 5 we see that the model now produces a weak positive correlation between researcher labor input in the R&D sector and GNP. The model correlation is now 0.05. This is close to the correlation of 0.1 that Barlevy (2007) reports for U.S. data. However he filters the data using a growth rate filter. If we use a growth rate filter instead the correlation produced by the model is 0.02. The sign of the model correlation is also positive at medium term cycle frequencies (see Table 7). The model's performance in other respects is similar to before. The correlation of R&D investment with output is still positive and of a similar magnitude to before. Correlations of equipment investment with output are also a bit lower. In addition the model now produces more consumption volatility. But in other respects the performance of the model is similar to the case with no adjustment costs on investment. As before these conclusions are also robust to the choice of the filter.

One distinction between the current parameterization and the parameterization with no adjustment costs on equipment is that productivity shocks to investment are more important now. With higher adjustment costs on equipment, bigger shocks are needed to reproduce the relative variability of investment. These shocks now have stronger effects on all forms of investment. Results reported in Table 6 indicate that equipment sector shocks now account for a majority of the variation in equipment investment in consumption units, about half of the variance in structures investment and over 80 percent of the variance in R&D investment. However, consumption goods shocks still play the primary role in moving the relative price of R&D. And this implies that the role of equipment sector shocks continues to account for only a small fraction of the variance in R&D investment expressed in consumption units. Equipment sector shocks now account for a larger fraction of the variance in equipment investment expressed in consumption units. However, equipment sector shocks continue to account for only a small fraction of the variance in output growth. In this parameterization, the price of equipment falls so much in response to equipment technology shocks that the value of equipment investment in consumption units falls (see Figure 4) and this acts to dampen the response of GNP to this type of shock.

5.1 Caveats

Before concluding we wish to mention several caveats. First, the model has counterfactual implications for the business cycle properties of the relative price of equipment. Our model predicts that the relative price of equipment is procyclical. For the specification with adjustment costs the value of this correlation is 0.35. This compares to a correlation of -0.26 using annual relative price data from Cummins and Violante(2002). Second, the model produces a negative correlation between investment in structures and investment in equipment expressed in consumption units. In U.S. data this correlation is 0.48. Our model with adjustment costs on equipment produces a correlation of -0.18.

There are a variety of extensions that could improve our model's fit in these dimensions. Allowing for endogenous variation in capacity utilization, modeling a labor supply decision and/or allowing shocks to technology among the two sectors to be correlated can all induce stronger comovements among sectors. Considering all of these possibilities is beyond the scope of this paper. We have, however, considered two of these extensions. If the two technology shocks have a positive correlation of 0.6, our model also produces a negative correlation between the relative price of equipment with output in U.S. data of -0.26..If we assume the correlation between our two technology shocks is 0.98, as Christiano and Fisher (2003) assume, our model implies that the correlation of structures and equipment is 0.40.

We have also generalized the model to allow for a labor supply decision for non-research labor. This generalization also enhances comovements across sectors. In particular, it generates a positive correlation of each type of non-research labor with GNP and also a positive correlation of R&D labor input with GNP.

6 Conclusion

We have produced a competitive model in which R&D investment is the engine of economic growth. Our model is different from the Romer (1990) model of R&D in that investment is under taken by perfectly competitive firms in our model and the resulting allocations are Pareto Optimal. We find that endogenous growth in R&D capital accounts for 75% of the growth rate of GNP and 75% of the average decline in the relative price of investment goods. Our results also suggest that one cannot rule out the possibility that pro-cyclical R&D is an optimal response to variations in the state of technology. In principal it is not difficult to produce pro-cyclical R&D investment and labor input to either consumption sector or equipment sector shocks. We have also shown that the quantitative properties of our model are good. The model reproduces some of the principal medium cycle facts and business cycle facts of the U.S. economy including both pro-cyclical R&D and pro-cyclical labor input in R&D.

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A Appendix

Here is a discussion of why its difficult/impossible to reproduce both output growth and the consumption share of output in our current model. Along a balanced growth path the following relationship holds:

$$\frac{P_{xH}x_H}{y^c} = \frac{\theta_h}{\alpha_h}\alpha_H \frac{h^h}{1-h^h}\frac{L_1 - L_1^h}{L_1^h}$$

If preferences are logarithmic we get:

$$\frac{P_{xH}x_H}{y^c} \approx \frac{\theta_h}{1-\alpha_h}\alpha_H \frac{L_1 - L_1^h}{L_1^h}$$

$$\gamma_{GNP} = \left(\beta\left(1+A_H\right)\right)^{1/(\sigma+\omega_H-1)} \tag{19}$$

$$\omega_H = \frac{1-\theta_k}{\theta_h}\frac{1-\alpha_h}{\alpha_H} - \frac{\alpha_k}{\alpha_H}$$

It is a challenge for the current theory to jointly match the average growth rate of GNP and consumptions share of output. Many of the parameters that act to increase consumption's share of output also lower the growth rate of GNP. If we consider the equation that governs GNP growth we can see that in the exponent either a small value of σ or a small value of ω_H are required to get higher GNP growth. A higher value of β and or A_H also can increase GNP growth.

Consider first the possibility of lowering ω_H. Notice that the inverse of the term $\frac{1-\alpha_h}{\theta_h \alpha_H}$ appears in the second equation. From this we see that lowering ω_H increases the share of R&D investment to output of the consumption good sector. We can ascertain the effect of a lower value of σ on equation two analytically. We know that h^h is decreasing in σ and that L_1^h is increasing in σ. Thus, a higher value of σ increases the relative size of the consumption good sector and lowers GNP growth. In Section 5 we report some computational experiments to see what happens to consumptions share of GNP. Starting from our baseline parameterization We lowered σ As the above equations suggest might be the case, we found that a lower value of sigma moved the consumption share of GNP and output growth in the opposite directions.

We have also tried some other experiments. For instance, we tried altering A_H. assuming log preferences over consumption ($\sigma = 1$). A lower value of A_H lowers GNP growth and also lowers $\frac{L_1 - L_1^h}{L_1^h}$ which lowers $\frac{P_{xH} x_H}{y^c}$.

Another possibility for increasing the consumption share is to lower $\frac{\theta_h}{\alpha_h}$. We conducted such an experiment where we reduced θ_h and increased θ_k to keep ω_H low. This increased GNP growth but lowered consumption's share of GNP. Instead structure's share of GNP increased. Altering other parameters such as α_h also move the growth rate of GNP and consumption's share of output in the opposite directions..

Table 1
Model Parameterizations

	Parameter	No adjustment costs on equipment investment	Adustment costs on equipment investment	Data facts used
Scale of Technology in R&D sector	A_H	0.0375	0.0375	fixed a priori
Structure share in consumption production	θ_k	0.12	0.12	fixed a priori
Equipment share in consumption production	θ_h	0.24	0.24	fixed a priori
Structure share in equipment production	α_k	0.08	0.08	first moments
Equipment share in equipment production	α_h	0.16	0.16	fixed a priori
R&D capital share in equipment production	α_H	0.45	0.45	first moments
Depreciation rate on structures	δ_k	0.0048	0.0048	average depreciation on structures
Depreciations rate on equipment	δ_h	0.0375	0.0375	average depreciation on equipment
Preference discount rate	β	0.992	0.992	fixed a priori
Relative Risk Aversion parameter	σ	3	3	Consumption share of output
Habit persistence parameter	b	0.4	0.4	volatility of consumption
Adjustment Costs to Structures Investment	φ_k	8.04	8.18	volatility of structures
Adjustment Costs to Equipment Investment	φ_h	0	7	fixed a priori
Adjustment Costs to R&D Investment	φ_H	0.7	0.7	fixed a priori
Autocorrelation Coefficent Consumption Technology	ρ	0.95	0.95	fixed a priori
Autocorrelation Coefficent Equipment Technology	ρ_h	0.95	0.95	fixed a priori
Shock Variance to Equipment Technology	v_h	1.60E-04	2.06E-03	volatility of equipment
Shock Variance to Consumption Technology	v_a	7.91E-05	7.80E-05	volatility of output

Table 2
First moment Properties of the model

Statistic	U.S. Data	Model (σ=3)	Model (σ=1)
Shares of Output			
Consumption	0.72	0.71	0.57
Equipment Investment	0.16	0.16	0.15
Structures Investment	0.093	0.036	0.045
R&D Investment	0.027	0.094	0.235
Labor Endowment Shares			
Researcher Labor Input in R&D	------	0.59	0.78
Non-researcher Labor Input in Equipment	------	0.1	0.1
Annualized Percentage Growth Rates			
Growth Rate of Output (annualized percentage	1.77	1.33	1.73
growth rate of relative price of equipment	4.52	3.43	4.44
growth rate of relative price of R&D	1.95	7.16	9.3

Table 3

Second Moment Properties U.S. data and Model at Business Cycle and Medium Term Cycle Frequencies*

No adjustment costs on equipment investment

	Relative Volatility				*Correlations with GNP*			
	Business Cycle Filter		Medium Cycle Filter		Business Cycle Filter		Medium Cycle Filter	
Variable	U.S. data	Model	U.S. data	Model	U.S. data	Model	U.S. data	Model
GNP	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Consumption	0.53	0.55	0.70	0.58	0.86	0.92	0.90	0.96
Investment	2.69	2.24	2.02	2.07	0.97	0.97	0.81	0.98
Structures Investment	2.63	2.63	2.43	6.39	0.69	0.38	0.57	0.77
Equipment Investment	3.67	3.67	2.67	2.58	0.92	0.81	0.75	0.65
R&D investment	1.03	2.24	2.54	2.20	0.67	0.61	0.15	0.72
Researcher Input in R&I	-----	1.65	-----	1.34	-----	-0.39	-----	-0.03

Table 4
Variance Decompositions

No adjustment costs on equipment investment*

Variable	*Percentage Variation Explained by Innovations to Technology in:*	
	Consumption sector	Equipment sector
GNP	99	1
Consumption	91	9
Investment	100	0
Structures Investment	84	16
Equipment Investment in consumption units	92	8
R&D Investment in consumption units	76	24
Researcher Labor Input in R&D	17	83
Non-Researcher input in Equipment	45	55
Equipment Investment	49	51
Relative price of Equipment Investment	66	34
R&D Investment	39	61
Relative Price of R&D investment	99	1

Table 5

Second Moment Properties U.S. data and Model at Business Cycle and Medium Term Cycle Frequencies*

Adjustment Costs on Equipment Investment, (φ_h =7)

	Relative Volatility				*Correlations with GNP*			
	Business Cycle Filter		Medium Cycle Filter		Business Cycle Filter		Medium Cycle Filter	
Variable	U.S. data	Model	U.S. data	Model	U.S. data	Model	U.S. data	Model
GNP	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Consumption	0.53	0.64	0.70	0.62	0.86	0.92	0.90	0.97
Investment	2.69	2.08	2.02	1.99	0.97	0.96	0.81	0.98
Structures Investment	2.63	2.63	2.43	7.71	0.69	0.34	0.57	0.76
Equipment Investment	3.67	3.67	2.67	3.01	0.92	0.53	0.75	0.44
R&D investment	1.03	3.70	2.54	2.82	0.67	0.62	0.15	0.59
Researcher Input in R&D	-----	2.35	-----	1.90	-----	0.05	-----	0.07

*Equipment nvestment and R&D investment are expressed in consumption units.

The business cycle filter emphasizes frequencies of 8 years or less. The Medium Cycle Filter emphasizes frequences of 50 years or less.

Table 6
Variance Decompositions

Adjustment Costs on Equipment Investment, (φ_h =7)*

Variable	*Percentage Variation Explained by Innovations to Technology in:* Consumption sector	Equipment sector
GNP	98	2
Consumption	79	21
Investment	92	8
Structures Investment	52	48
Equipment Investment in consumption units	32	68
R&D Investment in consumption units	72	28
Researcher Labor Input in R&D	3	97
Non-Researcher Labor Input in Equipment	5	95
Equipment Investment	1	99
Relative price of Equipment Investment	18	82
R&D Investment	11	89
Relative Price of R&D investment	98	2

Figure 1
Responses to Consumption Sector Technology Shock
No Adjustment Costs on Equipment Investment

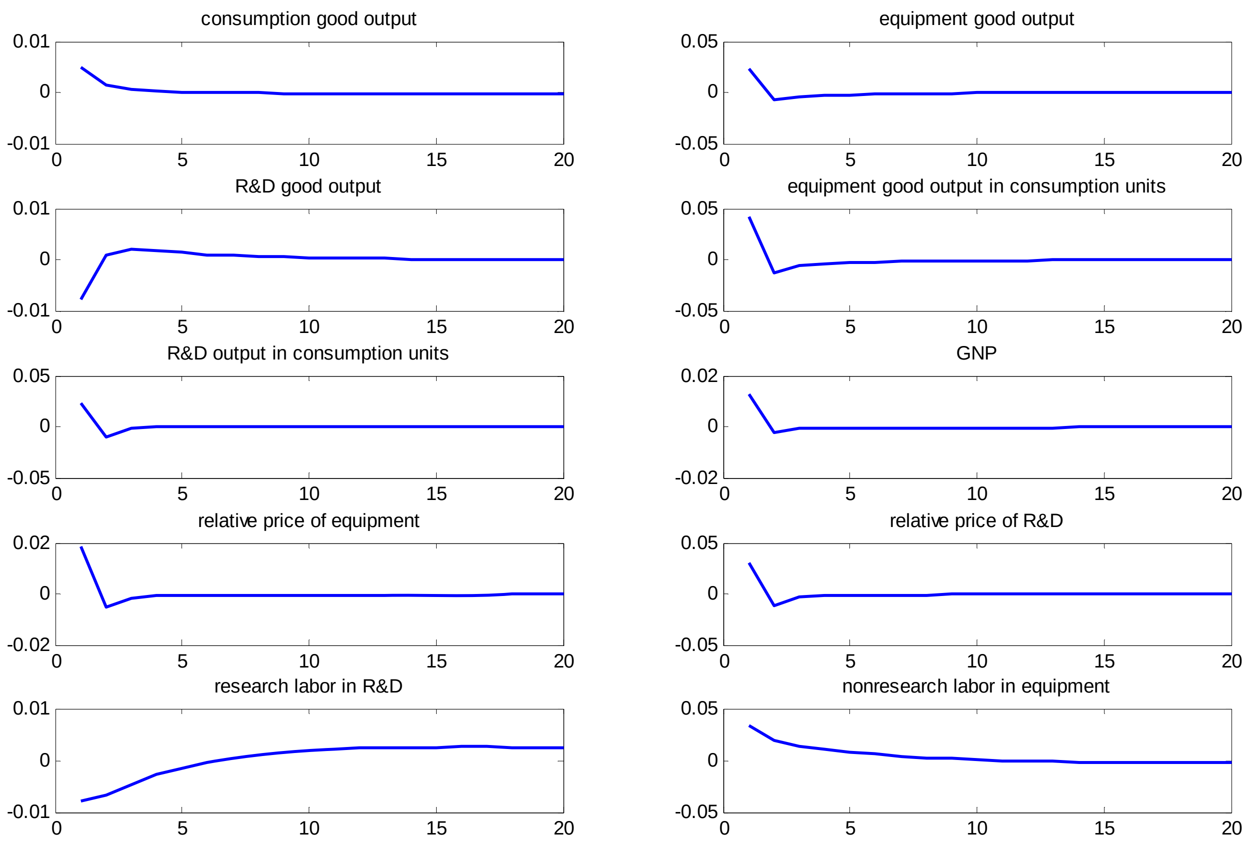

Figure 2
Responses to Equipment Sector Technology Shock
No Adjustment Costs on Equipment Investment

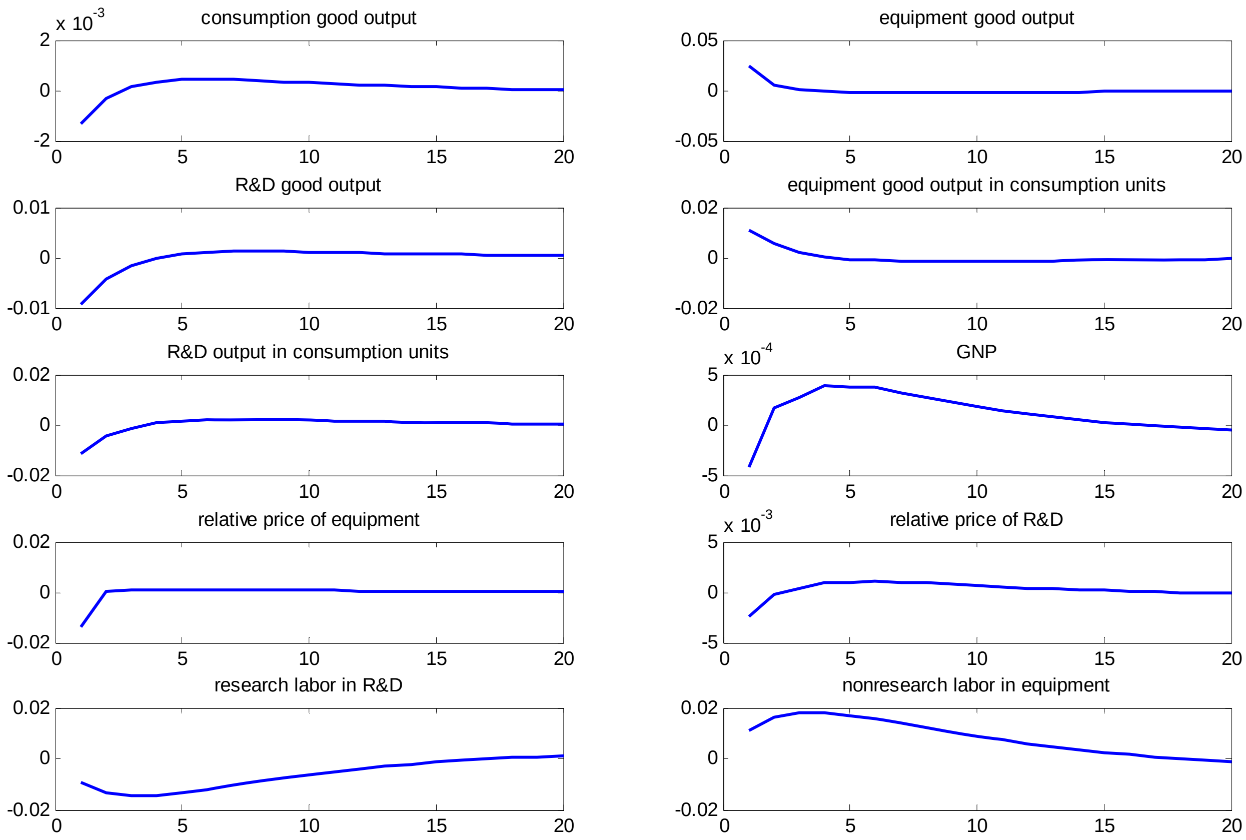

Figure 3
Responses to Consumption Sector Technology Shock with Adjustment Costs on Investment

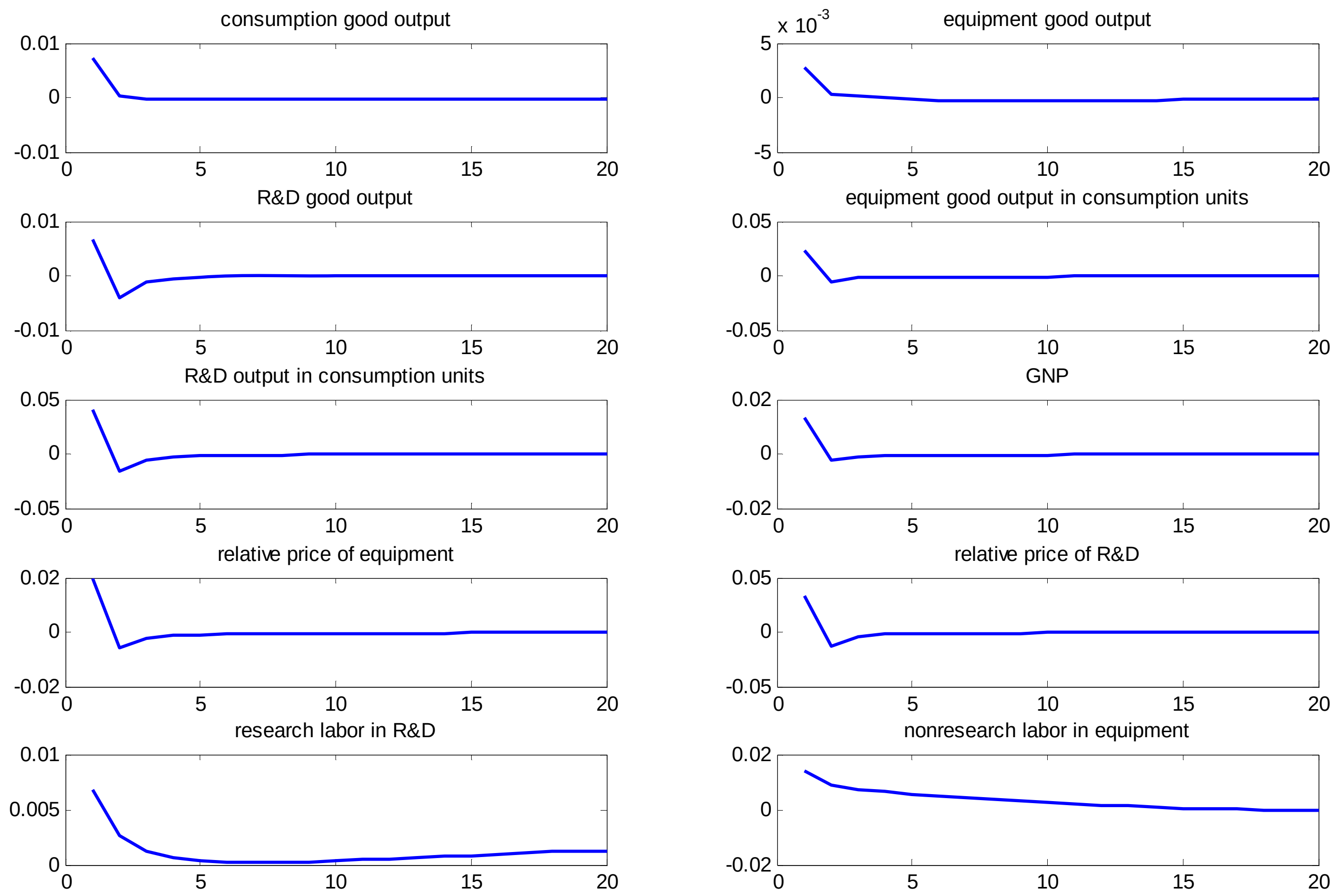

Figure 4
Responses to Equipment Sector Technology Shock with Adjustment Costs on Equipment Investment