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Growth, fluctuations and technology in the U.S. post-war economy

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Abstract. This paper explores several issues concerning how technology affects growth and fluctuations during several U.S. postwar series. The nature of technology is divided into neutral progress and investment-specific progress. Accounting for several changes in the first and second order moments of these series (the slowdown of productivity in 1974, the moderation of 1984 and the resurgence in productivity after 1994), I find that the contribution of investment-specific progress to growth has increased over time. I also find that neutral progress is crucial in explaining the cyclical component of output (before and after 1984), contrary to results found in related literature. However, the shocks to investment-specific progress have played an increasing role in output and other macroeconomic variables. Finally, I conclude that moderation in the macroeconomic series can be associated with technology. In sum, the quality of technological processes affecting long run growth and fluctuations has changed over the past decades.

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1 Introduction

This paper analyzes properties affecting the first and second order moments of the U.S. macroeconomic series in the past six decades. The economic literature has widely documented two important facts regarding first order moments: the productivity slowdown of 1974 (see Greenwood and Yorukoglu, 1997, among others), with a considerable decline in the growth rates of output compared to previous post-war periods; and that of 1995 onward, when both GDP growth and productivity growth showed an upsurge, a fact that has been associated with the rise of information technologies (see Collechia and Schreyer 2001; Stiroh 2002; Jorgenson, 2002). While the first episode was not exclusive to the U.S. economy (all other OECD economies also suffered a contraction in growth rates), the second episode has been more prominent in the U.S. than in other economies.

The volatility of U.S. GDP growth evinced a drastic reduction beginning in the first quarter of 1984 with regard to second order moments (McConnell and Pérez-Quirós, 2000; Stock and Watson, 2000). The volatilities of other GDP components and macroeconomic variables have also experienced sizable reductions. This has been called the great moderation. EU countries and the Japanese economy have experienced moderations of a smaller magnitude (Stock and Watson, 2005).

In the neoclassical model, long run productivity growth can only be driven by the state of technology. I adopt the view that the progress of technology can be caused by two complementary sources: neutral progress and investment-specific progress. While the former is associated with multifactor productivity, the latter refers to changes in the quality of investment goods. I use the series of quality adjusted prices of investment estimated by Gordon (1990) and later extended by Cummins and Violante (2002) to construct a proxy for investment-specific technological change. These quality adjusted prices also provide us with a series of neutral progress values, residually estimated from a Cobb-Douglas production function.

Using a calibrated DSGE model for the US economy, I investigate how observed changes in series of technology have contributed to changes in the properties of US aggregates. The changes are as follows. First, investment-specific technological progress has shown acceleration and neutral progress has shown deceleration since 1974. I will argue that this fact has had important implications for the evolution of average GDP growth since that date (see Greenwood and Yorukoglu, 1997; or Fisher, 2006). Indeed, neutral progress has played a secondary role in the evolution of productivity since 1974. Second, both series have become less volatile since 1984. Comparing the periods before and after 1984, I find moderation of the volatility of both forms of technological progress, accounting for between 1/4 and 1/3 of the total variance. This smoothing in the cycle of technology might have accounted for an important fraction of the reduction of business cycle volatility.

The main findings are as follows. First, long run growth has been led by investment-specific progress and, taking into account changes in the average growth of technology, the importance of investment-specific progress has increased over time. Second, most output deviations from the balanced growth path were caused by shocks to the neutral progress before 1974. The role of shocks in investment specific progress has increased since 1984, accounting for fluctuations of output and other macroeconomic variables. Output fluctuations, however, are led by shocks to neutral progress in both periods. For example, investment-specific shock before 1974 explains 6% of the unconditional variability of output and 27% of the variability of hours. After 1984, these values grow to 14% for output and 52% for hours. This finding is caused by alterations in the stochastic representations of both forms of technology. Third, while the related literature associates moderation with improvements in financial markets, good monetary policy practices, or good luck, I argue that such moderation can be (primarily but not solely) associated with technology. Finally, investment-specific technology has also played an increasing role in the conditional variances of these variables, both in short run and in long run horizons.

A number of studies relate to this paper. For instance, Greenwood, Hercowitz and Krusell (1997, 2000) decomposed the long run growth of output per hour worked using a series of hedonic prices for capital estimated by Gordon (1990) and found that investment-specific progress accounts for 58% of total growth across 1954-1990. They also used a calibrated model for the same period and found that 30% of output fluctuations are caused by the shock to investment-specific progress. These results were later extended and confirmed by Cummins and Violante (2002).

Within a similar framework, Pakko (2002) analyzed the transition dynamics due to changes in the growth rates of neutral and investment-specific technologies. The paper aimed to explain how changes in first order moments of technological progress may affect the long run adjustment of capital stock. Such changes induce firms to alter the optimal combination of capital and labor, resulting in a longer period during which observed productivity lags behind technology patterns. This explains the so called productivity paradox during the new economy age.

Arias, Hansen and Ohanian (2006) created a calibration exercise that analyzes the moderation in volatilities around 1984 using a variety of shocks: a TFP shock, a government spending shock, a shock affecting the substitution between consumption and labor, and a shock to the inter-temporal Euler equation. They estimate that the variances of these shocks were reduced after the first quarter of 1984 and show that a TFP shock (or a neutral technology shock) can respond substantially to the observed volatility declines in output and other macroeconomic variables. Note that this analysis only considers one form of technological progress, i.e., neutral progress, therefore neglecting the investment-specific channel.

A few recent econometric papers – Fisher (2006) and Justiniano and Primiceri (2008) –have also tackled the issue of moderation. According to the model of Greenwood et al. (1997, 2000), Fisher (2006) proposed a set of identifying conditions for the two technology shocks. In the long run, the relative price of investments is assumed to be affected solely by the investment-specific shock, while the growth rate of productivity is assumed to be affected by both types of shocks. The sample is divided into two subperiods, 1955.1-1979.2 and 1982.3-2000.4, where investment-specific shock is found to play a crucial role in accounting for hours and output fluctuations.

Justiniano and Primiceri (2008) estimated a DSGE model to analyze the different sources of U.S. fluctuations, which include shocks to technology (divided into neutral and investment-specific), shocks to preferences, fiscal shocks and nominal shocks. They did not use quality adjusted investment prices to construct a proxy measure of investment-specific technological shock. Instead, the model is estimated by considering all of these shocks unobservable. They found that investment-specific technological shock can account for most US output fluctuations and most of the decline in GNP volatility after 1984. They also found that the volatility of the series identified as technology stocks fell between 1/3 and 4/5 after 1984.

The structure of the paper is as follows. Section 2 presents the data and some preliminary evidence. A DSGE model with embodied technological progress is presented in Section 3. Sections 4 and 5 study the relationships between technology and the long run and the short run, respectively. Section 6 summarizes and concludes.

2 Data and preliminary evidence

Data on gross national product (GNP), consumption, investment and the official price index for investment in equipment come from the National Income and Product Accounts from the Bureau of Economic Analysis (NIPA-BEA)[1]. The aggregate hours index (PRS85006033) as a proxy for total hours worked[2] are from the Bureau of Economic Statistics (BLS).

I use the annual quality adjusted price index from Cummins and Violante (2000) for investment in equipment and annual quality adjusted depreciation rates of total capital. These series extend those previously calculated by Gordon (1989) to the year 2000. Following Fisher (2006) and Ríos-Rull et al. (2009), these annual series of quality adjusted prices are quarterlized using the method of Denton (1971), where quarterly fluctuations are those from the official price index for investments in equipment from the BEA Database (NIPA prices). This price index is used to extend the price series through 2001-2008. This allows us to analyze the period from 1948.1 to 2008.4.

Series of investments in structures and in equipment are aggregated using a Törnqvist index. As a deflator for the investment in structures, let us call P_t a Törnqvist price index of nondurables and services. As a deflator for investment in equipment, I use the extended quality adjusted price series from Gordon-Cummins-Violante. Both types of assets of investment include private and government expenditures. Investments in equipment also account for inventory changes and consumer durables expenditures. This provides us with

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[1] `http://www.bea.gov/index.htm`

[2] `http://www.bls.gov/`

an adjusted price index of total investment, which we call q_t. The investment-specific technological progress in capital is calculated as

$$Q_t = \frac{P_t}{q_t}, \tag{1}$$

which represents the amount of capital that can be purchased by one unit of output at time t.

Using a series of investment in terms of the consumption good (nondurable and service), the stock of capital is constructed from the law of motion,

$$K_{t+1} = (1-\delta) K_t + Q_t I_t, \tag{2}$$

where δ is Cummins-Violante's physical (quality adjusted) depreciation rate[3]. Following Ríos-Rull et al. (2009), I use an initial capital-output ratio of 11.6. Investment I_t is expressed in terms of the consumption good, while product $Q_t I_t$ expresses investment in efficiency units. Hence, total nominal investment (including both structure and equipment expenditures) is deflated using the Törnqvist price index of nondurables and services, P_t. The nominal GNP is also deflated using this index, P_t. Y_t is defined as the GNP in terms of the consumption good.

Finally, neutral technological change is computed as

$$A_t = \frac{Y_t}{L_t^{\alpha} K_t^{1-\alpha}}, \tag{3}$$

where L_t is total hours worked, measured by the aggregate index of hours from the BLS. From the BEA Database, the labor income share is $\alpha = 0.6515$.

The log levels of both series are plotted in figure 1, where the starting points have been normalized to one (similar plots can be found in Greenwood et al., 1997, and Pakko, 2002). Investment-specific technological change has been unambiguously increasing during the post-war decades, and the trend governing the level of neutral progress seems to have been exhausted after the mid-1970s, from 1974 onward.

[**Figure 1 here**]

Table 1 reports the average growth rates of both forms of technology for the total period under consideration (1948.1-2008.4) and four sub-periods, splitting the sample according to the following key years: the 1974 productivity slowdown (Greenwood and Yorukoglu, 1998), the great moderation year of 1984 (McConnell and Pérez-Quirós, 2000; Stock and Watson, 2000), and the acceleration from the new economy of 1995 (see Hansen, 2001, for structural break tests; or see Cummins and Violante, 2002 and Jorgenson and Stiroh, 2000, who

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[3] For the sake of simplicity, the rate of depreciation is written as a parameter, i.e. without a time subscript, although the rate provided by Cummins and Violante is an annual serie. For the years 2000-2008, I use a quarterly constant rate of 0.0145.

have stressed the importance of the ICT behind the resurgence in US productivity after 1995). These growth rates are presented in annualized terms. I highlight two facts in relation to this table. First, neutral technological progress has grown at a much slower rate on average (0.33%) than investment specific progress (2.54%). Second, this difference mainly arises after the 1974 recession, where neutral progress decelerates and investment-specific progress accelerates. Neutral progress has otherwise been growing at a negative rate close to zero (Greenwood and Yorukoglu, 1997).

Table 1: Average growth rates of technology

	Neutral, A_t	Inv.-Specific, Q_t
1948.1-2008.4	0.33	2.54
1948.1-1973.4	1.25	1.84
1974.1-1983.4	-0.46	2.15
1984.1-1994.4	-0.39	3.58
1995.1-2008.4	-0.22	3.30

Table 2 reports two volatility measures for technology (A_t and Q_t), output (GNP, Y_t), consumption of nondurables and services (C_t), investment (I_t, including private and public investments in both equipment and structures, change in inventories, and durable goods), hours per worker (h_t), number of workers (N_t, variable LNS12000000 of BLS), and total hours worked ($L_t = h_t N_t$, index PRS85006033 of BLS). The first panel shows the variances calculated according to a Hodrick-Prescott filter with a smoothing parameter of 1600, $HP \ln$, which isolates cycles shorter than 32 quarters. In the last panel of rows, variances are calculated according to the first difference of the log of the series, $\Delta \ln$, which isolates very short term fluctuations. All variances are scaled by a factor of 104. The last column of the table, labeled relative, presents the ratio of variances before and after 1984.1.

Comparing the periods before and after 1984, the variance of neutral progress is three to four times smaller and the variance of investment-specific progress is two to seven times smaller. HP-filtered series show an increase in variance during the period 1974.1-1983.4 compared to previous post-war years. This is not the case for neutral progress at higher frequencies, i.e., for the $\Delta \ln$ filter. Following some authors, I consider the first quarter of 1984 the switching point (McConnell and Pérez-Quirós, 2000 and Stock and Watson, 2000).

The variance of the macroeconomic variables also decreases after 1984.1. The strongest moderation is viewed for GNP. When the Hodrick-Prescott filter is used in the decomposition, volatility increases slightly during the decade 1974.1-1983.4 compared to the period before the 1974 slowdown. These variances do not substantially vary after 1995.1 compared to those computed for 1984.1-1994.1 (i.e., from the great moderation to the new economy age). The higher the frequency isolated by the filter, the greater the reduction in volatility. Whether the moderation of the main macroeconomic variables is due to technology is a question I will deal with in later sections.

Table 2: Variance of technology and macroeconomic variables ($\times 10^4$)

Hodrick-Prescott, $HP\ln$						
	1948.1-2008.4	48.1-73.4	74.1-83.4	84.1-94.4	95.1-08.4	Relative
Neutral, A_t	1.04	1.28	2.04	0.42	0.30	4.20
Inv.-Specific, Q_t	1.17	0.84	4.38	0.12	0.38	6.83
Output, Y_t	2.98	3.99	5.24	1.02	0.87	4.71
Consumption, C_t	1.59	1.84	3.08	0.67	0.64	3.36
Investment, I_t	33.62	41.28	61.78	15.08	12.76	3.44
Hours p.w. h_t	0.99	1.19	1.04	0.84	0.70	1.53
Workers, N_t	1.01	0.97	2.42	0.53	0.48	2.73
Hours, $L_t = h_t N_t$	3.40	3.51	6.34	2.36	1.97	2.03
First difference, $\Delta\ln$						
	1948.1-2008.4	48.1-73.4	74.1-83.4	84.1-94.4	95.1-08.4	Relative
Neutral, A_t	0.58	0.77	0.70	0.19	0.32	3.01
Inv.-Specific, Q_t	0.29	0.20	0.67	0.05	0.24	2.13
Output, Y_t	1.05	1.49	1.54	0.28	0.33	4.97
Consumption, C_t	0.71	1.07	0.83	0.30	0.27	3.58
Investment, I_t	12.52	17.86	20.39	4.68	3.67	4.52
Hours p.w. h_t	0.38	0.48	0.45	0.23	0.25	1.93
Workers, N_t	0.28	0.35	0.46	0.14	0.15	2.50
Hours, $L_t = h_t N_t$	0.83	1.00	1.38	0.42	0.44	2.43

3 The model

In this section I set up a standard DSGE model that describes the behavior of consumers and firms.

Households. The economy is inhabited by an infinitely lived, representative household that maximizes time-separable preferences in terms of consumption of final goods and hours worked, $\{C_t, L_t\}_{t=0}^{\infty}$, subject to budget restriction

$$\max_{\{C_t, I_t, L_t, K_{t+1}\}} E_0 \sum_{t=0}^{\infty} \beta^t \left(\ln(C_t) - \zeta \frac{L_t^{1+1/\nu}}{1+1/\nu} \right), \tag{4}$$

$$\begin{aligned} \text{s.t. } C_t + I_t &= W_t L_t + R_t K_t, & (5) \\ K_{t+1} &= (1-\delta) K_t + Q_t I_t, & (6) \end{aligned}$$

where K_0 is given, β is the time discount factor, ζ is a preference parameter affecting the substitution between consumption and leisure and υ is the Frisch labor supply elasticity. W_t and R_t denote the wage and the rental price of capital, respectively, and K_t denotes the amount of capital accumulated in terms of efficiency units. The budget constraint (5) faced by the consumer dictates that consumption and investments cannot exceed the sum of labor income and capital income. Capital holdings evolve according to (6) where δ is the physical depreciation rate and Q_t changes over time depending on the technological progress specific to this asset.

Firms. The production of output Y_t requires the services of labor L_t and capital K_t. Technology is given by a constant return to scale Cobb-Douglas production function, like the one introduced in (3). A problem for firms is finding optimal values for the utilization of labor and capital, taken as their respective prices W_t and R_t,

$$\max_{\{L_t, K_t\}} \left\{ A_t L_t^{\alpha} K_t^{1-\alpha} - W_t L_t - R_t K_t \right\}, \tag{7}$$

with $0 < \alpha < 1$ and where A_t is neutral technological change.

Feasibility. Final output can be used for two purposes: consumption or investment in capital,

$$Y_t = C_t + I_t. \tag{8}$$

Both output and investment are measured in units of consumption.

Technological progress. The two forms of technological progress under consideration $\{Q_t, A_t\}$ evolve according to

$$\begin{aligned} Q_t &= \left(1+\gamma_q\right)^t Q_0 \exp\left(u_{q,t}\right), & (9)\\ \phi_q\left(B\right) u_{q,t} &= \varepsilon_{q,t} \sim \mathcal{N}\left(0, \sigma_q^2\right), & (10) \end{aligned}$$

and

$$\begin{aligned} A_t &= \left(1+\gamma_a\right)^t A_0 \exp\left(u_{a,t}\right), & (11)\\ \phi_a\left(B\right) u_{a,t} &= \varepsilon_{a,t} \sim \mathcal{N}\left(0, \sigma_a^2\right), & (12) \end{aligned}$$

where $\phi_i\left(B\right)$, $i = a, q$, is an autoregressive polynomial of order p_i in the lag operator B, the roots of which lie outside the unit circle

$$\phi_i\left(B\right) = 1 - \sum_{j=1}^{p_i} \rho_{i,j} B^j. \tag{13}$$

Fundamental shocks are assumed to be orthogonal, $E\left(\varepsilon_{q,t}\varepsilon_{a,t}\right) = 0$.

A common assumption is that both processes are AR(1), $p_a = p_q = 1$, so that $\phi_i\left(B\right) = 1 - \rho_i B$ and the persistency of $\varepsilon_{i,t}$ on the level of their respective technological progress is determined by ρ_i. If $\rho_i = 1$, the process is governed by stochastic trends and shocks $\varepsilon_{i,t}$ have permanent effects on the *level* of technology and productivity, a property exploited by Fisher (2006) to identify technology shocks, $Q_t = \exp\left(\gamma_q + \varepsilon_{q,t}\right) Q_{t-1}$ and $A_t = \exp\left(\gamma_a + \varepsilon_{a,t}\right) A_{t-1}$.

Euler equations. The first order conditions can be summarized in the following four equations:

$$\begin{aligned} L_t &= \left(\frac{1}{\zeta}\frac{W_t}{C_t}\right)^{\upsilon}, & (14)\\ 1 &= \beta E_t\left[\frac{C_t}{C_{t+1}}\frac{Q_t}{Q_{t+1}}\left(Q_{t+1}R_{t+1} + 1 - \delta\right)\right], & (15)\\ R_t &= \left(1-\alpha\right)\frac{Y_t}{K_t}, & (16)\\ W_t &= \alpha\frac{Y_t}{L_t}. & (17) \end{aligned}$$

Condition (14) is the result that equates the marginal rate of substitution between consumption and leisure to the opportunity cost of one additional unit of leisure. Expression (15) implies that the inter-temporal marginal rate of substitution is equal to the rate of investment asset return. In (16) and (17), the firm hires capital and labor such that the marginal contributions of these factors must equal their rental prices.

Equilibrium. A competitive equilibrium for this economy is a sequence of consumption, labor and private investment acts for consumers $\{C_t, L_t, I_t\}_{t=0}^{\infty}$, a sequence of capital and labor utilizations for firm $\{K_t, L_t\}_{t=0}^{\infty}$, and a sequence of states of technology $\{A_t, Q_t\}_{t=0}^{\infty}$, such that given a sequence of prices $\{W_t, R_t\}_{t=0}^{\infty}$*(i)* the optimization problem of the consumer is satisfied, (14)-(15); *(ii)* the first order conditions of the firm hold, (16)-(17); and *(iii)* the feasibility constraint of the economy holds (8).

Calibration. The following expressions characterize the steady state conditions of the economy

$$\begin{aligned}
\frac{1+\gamma}{\beta} &= \frac{1}{1+\gamma_q}\left[(1-\alpha)\frac{Q_{ss}Y_{ss}}{K_{ss}}+1-\delta\right], && (18)\\
(1+\gamma_q)(1+\gamma) &= \left(\frac{Q_{ss}Y_{ss}}{K_{ss}}\right)\left(\frac{I_{ss}}{Y_{ss}}\right)+1-\delta, && (19)\\
1 &= \frac{C_{ss}}{Y_{ss}}+\frac{I_{ss}}{Y_{ss}}, && (20)\\
L_{ss} &= \left(\frac{\alpha}{\zeta}\frac{Y_{ss}}{C_{ss}}\right)^{\upsilon/(1+\upsilon)}. && (21)
\end{aligned}$$

The subscript ss expresses the steady state position and γ is the balanced growth rate of output, consumption and investment.

The following set of parameters and steady state ratios need to be calibrated:

$$\gamma, \gamma_q, \alpha, \delta, \beta, \upsilon, \zeta, \frac{C_{ss}}{Y_{ss}}, \frac{Q_{ss}Y_{ss}}{K_{ss}}. \qquad (22)$$

Using the data described in section 2, I use

$$\begin{aligned}
\gamma &= 1.01769^{1/4}-1 = 0.0044, && (23)\\
\gamma_q &= 1.02540^{1/4}-1 = 0.0063. && (24)
\end{aligned}$$

From the national accounts, I use labor income ratio $\alpha = 0.6515$. This share is consistent with that provided by Gollin (2002), who estimates that the income share should be within the interval [0.65,0.80] in a wide set of countries under consideration. In similar exercises, Greenwood et al. (1997, 2000) and Pakko (2002) use $\alpha = 0.7$, Fisher (2006) uses $\alpha = 2/3$, Arias et al. (2007) use $\alpha = 0.6$, and Ríos-Rull et al. (2009) use $\alpha = 0.6515$. From Cummins and Violante (2002), the depreciation rate averaged through the complete period is $\delta = 0.0135$. Taking an annual real rate of return of 4%, the time discount factor is $\beta = (1+\gamma)/1.04^{0.25} = 0.9948$.

The Frisch elasticity of the supply of hours is assumed to be $\upsilon = 2$. For the complete sample, 1954.3-2004.4, Justiniano and Primiceri (2008) suggest $\upsilon = 1/2$ as a Bayesian prior mean and estimate a posterior median of $\upsilon = 1/1.59$. Ríos-Rull et al (2009) provide a comprehensive analysis of the value of this elasticity. They also assume in their Bayesian estimation a prior of $\upsilon = 2$. A value of $\zeta = 4.7287$ is assigned to produce a non leisure steady state time fraction of 1/3.

Expressions (18) and (19) yield $Q_{ss}Y_{ss}/K_{ss} = 8.522 \times 10^{-2}$. Accordingly, the ratio I_{ss}/Y_{ss} is estimated as 0.2841, with an observed average investment to output ratio over 1948.1-2008.4 equal to 0.2834.

4 Technology and growth

Along a balanced growth path, output, consumption and investment must all grow at the same rate, denoted by γ. As hours worked will not increase, the implied balanced growth from the (log-linearized) production function is $\gamma \simeq \gamma_a + (1-\alpha)\gamma_k$, where γ_k denotes the steady state growth rate of capital. The long run growth rate of output can be accounted for by neutral technological progress γ_a and by increases in capital stock γ_k. From the law of motion (6), the long run growth rate of capital is $\gamma_k \simeq \gamma_q + \gamma$. Therefore, it is possible to express output growth as a function of the exogenous growth rates of technologies as

$$\gamma = \frac{1}{\alpha}\gamma_a + \frac{1-\alpha}{\alpha}\gamma_q. \tag{25}$$

For growth accounting purposes, it is convenient to rewrite this expression as:

$$1 = \underbrace{\frac{\gamma_a}{\gamma_a + (1-\alpha)\gamma_q}}_{\text{Neutral}} + \underbrace{\frac{(1-\alpha)\gamma_q}{\gamma_a + (1-\alpha)\gamma_q}}_{\text{Investment-specific}}. \tag{26}$$

Fisher (2006) uses this expression to identify the sources of technical progress on the balanced growth path. Note that the higher the labor share α, the smaller the contribution from investment specific progress and the larger the contribution from neutral change. Also, when $\gamma_a > 0$, the highest possible impact of investment specific progress is bounded by $\gamma_q/\left(\gamma_a + \gamma_q\right)$.

Table 3 reports the decomposition of growth in annualized output per hour worked according to expressions (25) and (26). The observed growth rate of the period and the rate calibrated according to expression (25) are reported. In all periods except the last one, the growth rate predicted by the model is higher than the observed rate, although the differences are negligible. The last two rows present decomposition according to (26).

Based on this table, I conclude that, first, the growth rate of output per hour worked is dominated by investment-specific technological change. Neutral technological change can only account for 27% of productivity growth across the total period, while 72% of total growth is caused by investment specific technological change. This is higher than the 58% share provided by Greenwood et al. (1997) for 1954-1990 or by Cummins and Violante (2002) for 1948-2000.

A second interesting conclusion from Table 3 concerns the increasing role played by investment-specific progress. The dashed lines in the last two rows indicate that the contribution of neutral change to growth has been negative. This is a consequence of the deceleration in neutral change and the acceleration of specific progress beginning in 1974, as highlighted in table 1.

Table 3: Technological sources of growth

Period	**1948-08**	**1948-73**	**1974-83**	**1984-94**	**1995-08**
Output per hour					
Observed	1.77	2.66	0.81	0.81	1.66
Calibrated, $(a + b)$	1.87	2.93	0.88	1.29	1.41
Neutral (a)	0.51	1.93	-0.65	-0.60	-0.34
Specific (b)	1.35	0.98	1.54	1.90	1.75
Contribution					
Neutral, $(a)/(a+b)$	27.4%	66.4%	–	–	–
Specific, $(b)/(a+b)$	72.6%	33.6%	–	–	–

5 Technology and fluctuations

I next identify the representation of the cyclical components affecting the two technological processes. This implies the identification of the autoregresive polynomial order $\phi_i(B)$ in (13), AR(p). For this purpose, a likelihood ratio (LR) test is applied for the complete sample and for three subsamples of 1948.1-1973.4, 1974.1-1983.4 and 1984.1-2008.4. The LR test suggests an AR(1) process for the cyclical component of neutral technology, u_{at}.[4] This order is stable when the sample is split into the three subsamples. For the cyclical component of investment specific technology, u_{qt}, the LR test suggests an order of three lags for the complete sample, four lags for the subsample 1948:1-1973.4, and two lags for the other subsamples, 1974.1-1983.4 and 1984.1-2008.4.

Using maximum likelihood I estimate the set of parameters for the complete sample and for the three partitions of the sample. The estimates are shown on table 4. Numbers in parentheses represent standard deviations. The first three rows of table 4 estimate an AR(1) for the neutral process $\phi_a(B) = 1 - \rho_a B$. The evolution of σ_a reflects the moderation of neutral technology: the standard deviation in the first sample, 1948.1-73.4, is smaller by a factor of 1.69 compared to that of the last sample, 1984.1-08.4. The evolution of γ_a reflects deceleration in neutral progress, primarily after the 1974 slowdown.

The last rows of table 4 present estimates for the process of investment specific progress. For the entire sample, roots in the autoregressive polynomial are outside the unit circle. The persistency gradually increases from the first

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[4] The null of one lag cannot be rejected at 5% when the alternative moves from two to five lags. In all cases the statistic are well below the critical region.

to the last split of the sample, $\sum_{j=1}^{p_i} \rho_{i,j}$. In the last subsample, the null of a unit root cannot be rejected, and a different stationary trend is imposed by assuming $\rho_{q1} = 1 - \rho_{q2}$. Importantly, in contrast to the previous estimates of table 2, the estimated standard deviations vary little across sub-samples. The variance of neutral shock is always higher than that of investment-specific shock, but the ratio σ_a^2/σ_q^2 reduces from 8.8 to 2.3. decreases from 8.8 to 2.3. This reduction in volatility, together with the increase in persistency, indicates that investment-specific shock may have gained strength in explaining short run fluctuations after 1984.[5] Finally, note that the upward evolution of γ_q reflects an acceleration in the quality improvements of investment goods

Table 4: ML estimation II

	1948.1-2008.4		1948.1-1973.4		1974.1-1983.4		1984.1-2008.4	
ρ_a	0.9832	(0.0070)	0.8339	(0.0543)	0.9015	(0.0694)	0.8659	(0.0510)
γ_a	-0.001	(0.0007)	0.0029	(0.0002)	-0.002	(0.0012)	-0.0007	(0.0001)
σ_a	0.0073	(0.0001)	0.0083	(0.0001)	0.0073	(0.0001)	0.0049	(0.0000)
ρ_{1q}	1.8753	(0.0679)	1.7211	(0.0952)	1.6902	(0.0661)	1.6952	(0.0986)
ρ_{2q}	-1.033	(0.1266)	-0.676	(0.1893)	-0.814	(0.0647)	-0.6952	–
ρ_{3q}	0.1509	(0.0674)	-0.273	(0.1890)	–	–	–	–
ρ_{4q}	–	–	0.2090	(0.0938)	–	–	–	–
γ_q	0.0075	(0.0005)	0.0054	(0.0007)	0.0067	(0.0004)	0.0078	(0.0011)
σ_q	0.0034	(0.0000)	0.0028	(0.0000)	0.0029	(0.0000)	0.0032	(0.0000)

In table 4, unless otherwise noted for the period 1948.1-1973.4, I use the following parameters $\rho_a = 0.834$, $\gamma_a = 0.003$, $\sigma_a = 0.0083$, $\gamma_q = 0.0054$, $\rho_{1q} = 1.72$, $\rho_{2q} = -0.67$, $\rho_{3q} = -0.27$, $\rho_{4q} = 0.21$ and $\sigma_q = 0.003$; and for the period 1984:1-2008.4, $\rho_a = 0.866$, $\gamma_a = -0.0007$, $\sigma_a = 0.0049$, $\rho_{1q} = 1.6952$, $\rho_{2q} = -0.6952$ and $\sigma_q = 0.003$.

Using a second order extension of the model (see Schmitt-Grohè and Uribe, 2002), figure 2 plots the responses of output, consumption, investment, hours and capital, respectively, to an orthogonal standard deviation impulse on both shocks. A positive shock to neutral progress, $\varepsilon_{a,t}$, has a positive impact on output by raising total factor productivity A_t (fig. 2.1). In response to this shock, consumption and investment increase due the effects on income: both labor revenues and capital revenues must increase (fig. 2.2 and 2.3). The response of hours to a positive shock to neutral progress, $\varepsilon_{a,t}$, depends on the Frisch labor supply elasticity υ (fig. 2.4). The higher this elasticity, the higher the response of labor to an increase in wage. As the marginal product of labor increases after a shock $\varepsilon_{a,t} > 0$, the increase in hours worked must be affected by the isoelasticity of the labor supply, $\upsilon \geq 0$. Labor productivity increases in response to a positive shock to neutral progress, $\varepsilon_{a,t}$ (fig. 2.6).

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[5] Fisher (2006) splits the sample and estimates $\sigma_a = 0.0115$ and $\sigma_q = 0.0116$ for 1955.1-1979.2, and $\sigma_a = 0.005$ and $\sigma_q = 0.0033$ for 1982.3-2000.4. Albeit some similarities to our estimations exists, note that neither the ratios σ_a/σ_q nor the magnitude of moderation is similar.

A positive shock to investment-specific progress, $\varepsilon_{q,t}$, affects the marginal product of capital and its rate of return, implying an inter-temporal substitution in consumption and an intratemporal substitution between consumption and leisure. Therefore, investments increase due to increases in returns (fig. 2.3). The labor supply also increases given that the increase of capital efficiency positively affects the marginal product of labor (fig. 2.4). Output is therefore affected in the current period through the impacts on labor supply and investment decisions (fig. 2.1). In the following and subsequent periods, a positive shock to investment-specific progress, $\varepsilon_{q,t}$, induces the marginal product of capital. In response to investment-specific shock, there is an increase in investment and a simultaneous decrease in consumption (fig. 2.2 and 2.3); at a given wage, leisure decreases as well. Note that because the elasticity of output with respect to labor is smaller than one $\alpha < 1$, a 1% increase in the amount of hours worked increases output less than proportionally in the short run. Note its negative immediate impact on productivity. As this shock affects the marginal product of capital, labor productivity also increases in the medium term (after 4-6 quarters, fig. 2.6). In response to both shocks, investment experiences a contemporary increase that later dies out, and capital accumulation increases during current periods and those following the shock occurrences (fig. 2.5).

Figure 3 plots the impulse response functions according to the data for 1984.1-2008.4 in table 4. The effect of investment specific shock is now more persistent than that of shock to neutral progress. In the short run, however, all variables except for capital stock seem to be more responsive to neutral shock.

[**Figures 2 and 3 here**]

In table 5, the unconditional variances are calculated by simulating the model with two sets of parameters for the periods 1948.1-1973.4 and 1984.1-2008.4. As my interest is focused on how changes in the variances affect the decision rules of the agents, I take a second order approximation of the model following Schmitt-Grohè and Uribe (2002). Within the simulation representing each period, I calculate the variances with only shocks to neutral progress ($\sigma_a > 0$, $\sigma_q = 0$) or with only shocks to investment specific technology ($\sigma_a = 0$, $\sigma_q > 0$) using both types of shocks ($\sigma_a > 0$, $\sigma_q = 0$). The model is simulated for time length $T = 25000$ and uses a HP-filter and a difference-filter for the simulated variables to calculate their variances. These simulated variances are divided by those observed in the data for the periods 1948.1-1973.4 and 1984.1-2008.4. Variables are detrended accordingly.

I highlight the following results. For the simulation representing the first period, 1948.1-1973.4, all variances except consumption decrease when either σ_a or σ_q is removed. However, most of this moderation is due to the volatility of shock to neutral progress, σ_a, ceteris paribus, with the remaining parameters held constant. When these unconditional variances are decomposed, the shock to neutral progress accounts for most of the variability in output (more than 90%), investment (more than 80%) and hours (more than 75%). Investment specific shock can explain 80% of the variability in consumption and 25% of the variance in hours.

Things are different for the second period, 1984.1-2008.4. Output variability is still dominated by shock to neutral technology. For the other variables, investment specific shock has a more decisive role that varies from 40% for investments to 50% for hours and 90% for consumption. The role of shocks in investment specific technology increases in all cases: about 10% for output and consumption and about 25% for investment and hours. These results are similar to those obtained by Victor et al. (2009), who found that while output variability is dominated by the shock to neutral technology, variance in hours is dominated by the shock to investment-specific progress.

Comparison of the two periods reveals that technology itself can account for most of the reduction in volatility of the series (see table 2), although there is an additional wedge left uncovered (i.e., the simulated moderation in table 5 is smaller than the observed moderation in table 2). For example, using the HP-filter, the variance of simulated output is reduced by a factor of 2.75, while the output observed in the data is reduced by a factor of 4.3. In order to test the null hypothesis of a change in this ratio, I construct the $F-$statistic

$$\frac{n_2 - 1}{n_1 - 1} \frac{n_1}{n_2} \frac{\sigma_1^2/\sigma_2^2}{s_1^2/s_2^2} \sim \mathcal{F}\left(n_1 - 1, n_2 - 1\right),$$

where σ_1^2 and σ_2^2 are the variances in the data for the periods 1948.1-1973.4 and 1984.1-2008.4 (table 2), respectively, with sample sizes $n_1 = 103$ and $n_2 = 100$. The pair of s_1^2 and s_2^2 represents variances simulated according to the calibrated model for the two periods. This test checks for possible breaks in the ratio of simulated to observed variances that may indicate changes in the transmission mechanism of the model. The last column of table 5 presents the $p-$value according to this test. For both filters, the p-values show that the statistics are well above the 10% critical value for consumption and investment. For output, the test fails to reject the null at the 2% significance level when the HP filter is used. Importantly, the null is not rejected for hours, even though the role of the investment specific technology shock in accounting for the variance has strengthened.

Table 5: Predicted versus observed unconditional variances

	1948.1-1973.4			1984.1-2008.4			p-value
	$\sigma_a > 0$ $\sigma_q = 0$	$\sigma_a = 0$ $\sigma_q > 0$	$\sigma_a > 0$ $\sigma_q > 0$	$\sigma_a > 0$ $\sigma_q = 0$	$\sigma_a = 0$ $\sigma_q > 0$	$\sigma_a > 0$ $\sigma_q > 0$	
Hodrick-Prescott, $HP \ln$							
Output	0.67	0.04	2.83/4.00=0.71	0.94	0.16	1.03/0.93=1.10	0.02
Consumption	0.04	0.15	0.33/1.81=0.18	0.05	0.35	0.26/0.66=0.40	0.00
Investment	0.56	0.13	28.5/41.3=0.69	0.70	0.50	16.6/13.8=1.20	0.00
Hours	0.27	0.10	1.31/3.51=0.37	0.14	0.15	0.61/2.12=0.29	0.10
First difference, $\Delta \ln$							
Output	1.34	0.04	2.04/1.49=1.37	2.12	0.31	0.75/0.31=2.42	0.00
Consumption	0.02	0.09	0.12/1.07=0.11	0.05	0.60	0.18/0.28=0.65	0.00
Investment	0.97	0.10	19.2/17.8=1.08	1.78	1.18	12.1/4.1=2.96	0.00
Hours	0.72	0.12	0.84/0.99=0.84	0.49	0.49	0.44/0.45=0.98	0.22

Period 1948.1-1973.4: $\rho_a = 0.834$, $\gamma_a = 0.003$, $\sigma_a = 0.0083$,
$\gamma_q = 0.005$, $\rho_{1q} = 1.72$, $\rho_{2q} = -0.67$, $\rho_{3q} = -0.27$, $\rho_{4q} = 0.21$, $\sigma_q = 0.003$.
Period 1984.1-2008.4: $\rho_a = 0.86$, $\gamma_a = -.0007$, $\sigma_a = 0.005$,
$\gamma_q = 0.008$, $\rho_{1q} = 1.6952$, $\rho_{2q} = -0.6952$, $\sigma_q = 0.003$.

Table 6 presents a decomposition of the conditional variance of forecast errors. I again choose two sets of parameters: those corresponding to 1948.1-1973.4 (upper panel) and those for 1984.1-2008.4 (lower panel). In the upper panel, the scenario associated with the period before slowdown and moderation, all variables appear to be governed by the shock to neutral progress at short term horizons. The other shock accounts for a non negligible fraction of all of these variances, except that of output. At medium and long term horizons, investment-specific shock helps explain an important fraction of these variances.

In the lower panel of table 6, all variables (except consumption) in the short run are heavily influenced by neutral shock, while they are governed by investment specific technological shock in the medium and long runs. With respect to the upper panel, the importance of shocks to investment specific technology seems to have increased in the years following 1984. This conclusion applies to both the unconditional variances in table 5 and the conditional variances in table 6.

Table 6: Decomposition of conditional variances

	Output		Consumption		Investment		Hours	
Horizon	$\varepsilon_{a,t}$	$\varepsilon_{q,t}$	$\varepsilon_{a,t}$	$\varepsilon_{q,t}$	$\varepsilon_{a,t}$	$\varepsilon_{q,t}$	$\varepsilon_{a,t}$	$\varepsilon_{q,t}$
1	99.9	0.1	89.4	10.6	99.6	0.4	99.4	0.6
4	94.4	5.6	29.8	70.2	80.8	19.2	72.1	27.9
16	81.1	18.9	54.8	45.2	61.2	38.8	50.9	49.1
40	72.2	27.8	46.5	53.5	59.4	40.6	50.9	49.1
150	69.8	30.2	36.5	63.5	59.3	40.7	50.0	50.0

Period 1948.1-1973.4: $\rho_a = 0.834$, $\gamma_a = 0.003$, $\sigma_a = 0.0083$, $\gamma_q = 0.005$, $\rho_{1q} = 1.72$, $\rho_{2q} = -0.67$, $\rho_{3q} = -0.27$, $\rho_{4q} = 0.21$, $\sigma_q = 0.003$.

	Output		Consumption		Investment		Hours	
Horizon	$\varepsilon_{a,t}$	$\varepsilon_{q,t}$	$\varepsilon_{a,t}$	$\varepsilon_{q,t}$	$\varepsilon_{a,t}$	$\varepsilon_{q,t}$	$\varepsilon_{a,t}$	$\varepsilon_{q,t}$
1	93.2	6.8	14.2	85.8	73.6	26.4	65.4	34.6
4	96.7	3.3	43.6	56.4	84.8	15.2	78.3	21.6
16	74.5	25.5	59.3	40.7	49.0	51.0	39.7	60.3
40	36.1	63.9	33.6	66.4	32.2	67.8	30.3	69.7
150	7.8	92.2	2.8	97.2	21.0	79.0	29.5	70.5

Period 1984.1-2008.4: $\rho_a = 0.86$, $\gamma_a = -.0007$, $\sigma_a = 0.005$, $\gamma_q = 0.008$, $\rho_{1q} = 1.6952$, $\rho_{2q} = -0.6952$, $\sigma_q = 0.003$.

6 Concluding remarks

This paper investigates the contributions of different sources of technological progress to US GNP growth and its volatility. I have used a DSGE model that decomposes productivity growth into two sources of technological progress: neutral and investment-specific change. The first type of progress refers to changes affecting total factor productivity, and the second type refers to changes in the quality of investment goods.

The conclusions are as follows. US long run growth has been led by investment-specific progress and its contribution has increased over time, insomuch as this progress has accelerated. Most of the deviations in output and investment from the balanced growth path have been caused by shocks to neutral progress. However, shocks to investment specific technological change account for an important fraction of the variability in consumption and hours. This finding applies to both unconditional and conditional variances. Third, when changes affecting the representations of technology in 1974 and 1984 are taken into account, the role of shocks to investment specific progress increases over time for all variables. I also conclude that the moderation in volatility of the macroeconomic series can be primarily explained through technology arguments.

These findings suggest that the nature of growth and fluctuations has changed as the essence of technology has evolved over the past three decades.

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Figures

Figure 1: Technological Progress

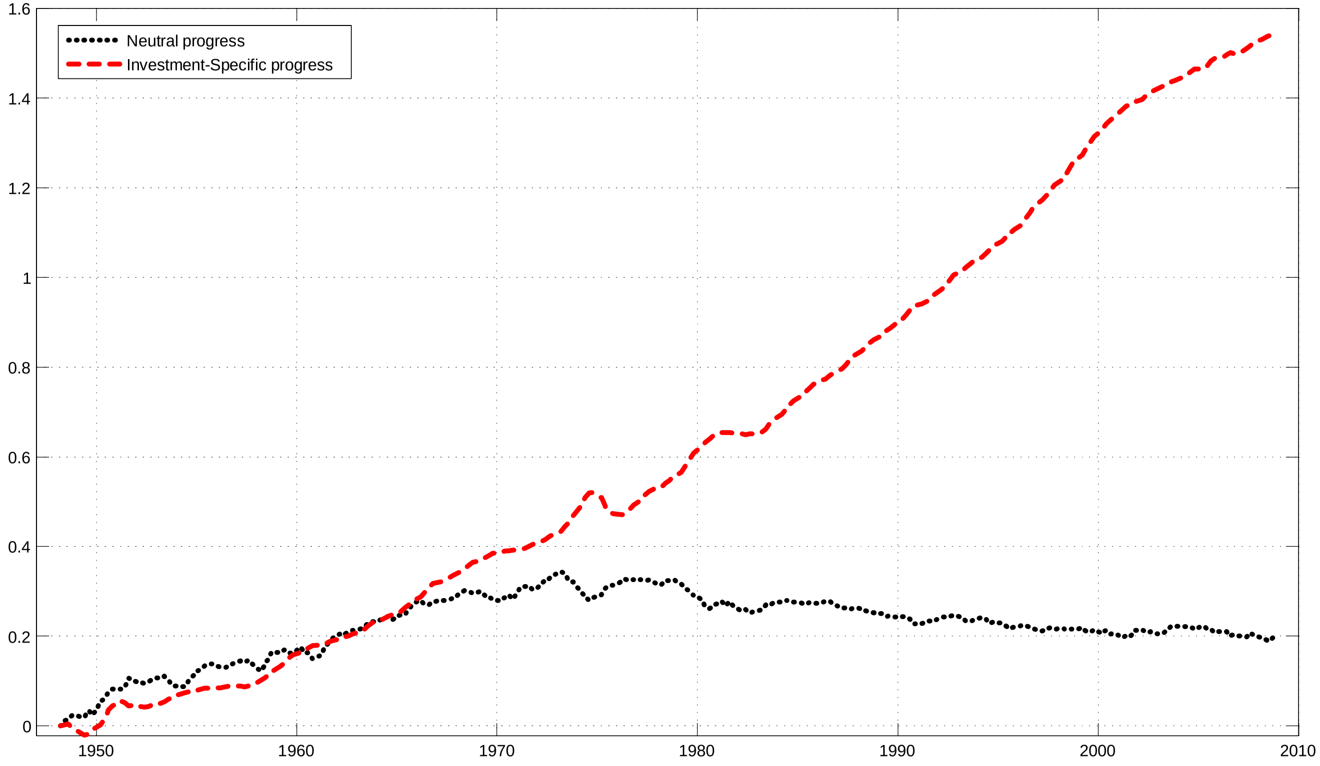

Figure 2.1: Impulse-Responses of Output

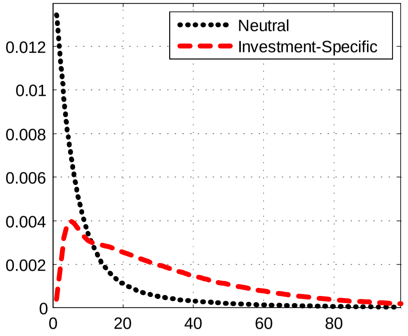

Figure 2.2: Impulse-Responses of Consumption

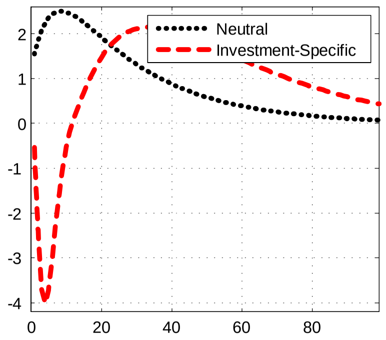

Figure 2.3: Impulse-Responses of Investment

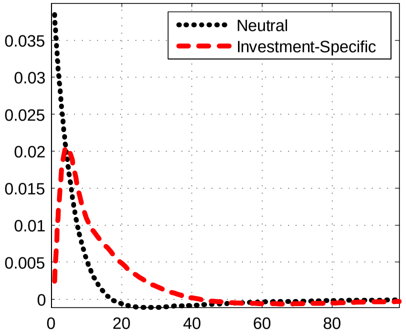

Figure 2.4: Impulse-Responses of Hours

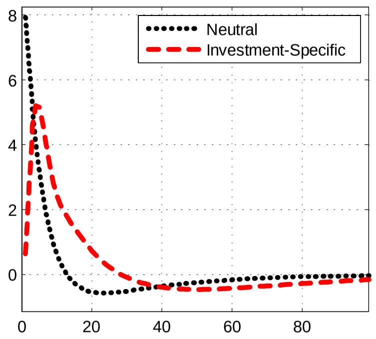

Figure 2.5: Impulse-Responses of Capital

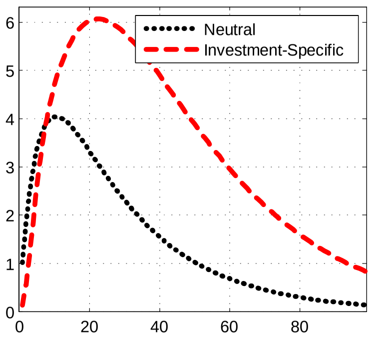

Figure 2.6: Impulse-Responses of Productivity

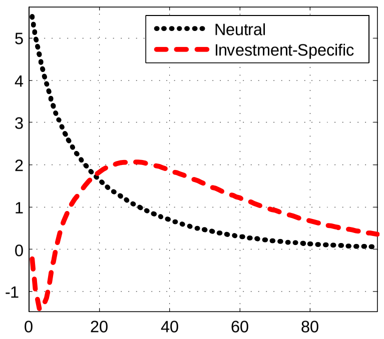

Figure 3.1: Impulse-Responses of Output

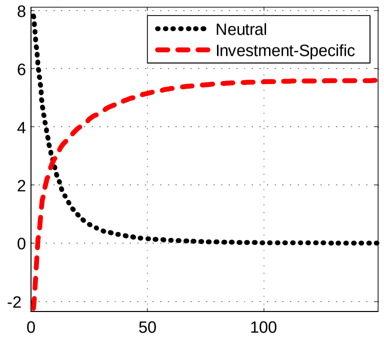

Figure 3.2: Impulse-Responses of Consumption

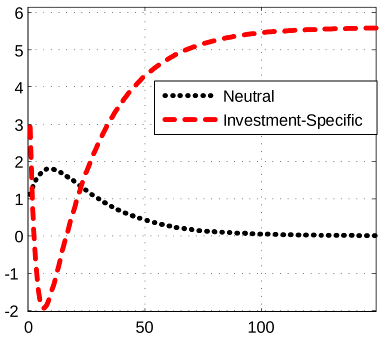

Figure 3.3: Impulse-Responses of Investment

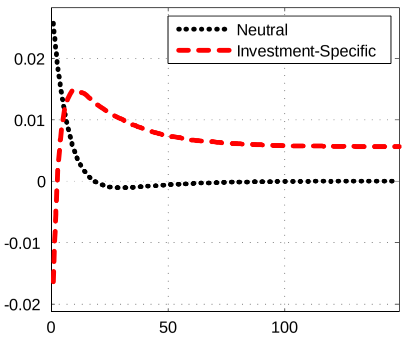

Figure 3.4: Impulse-Responses of Hours

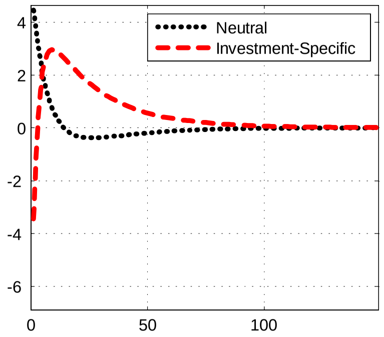

Figure 3.5: Impulse-Responses of Capital

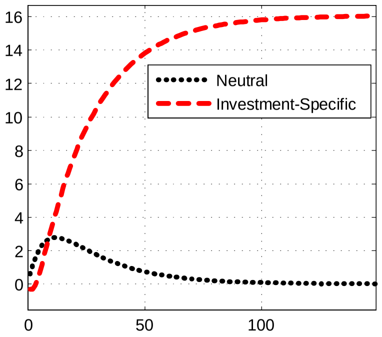

Figure 3.6: Impulse-Responses of Productivity