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Technology Creation, Diffusion, and Growth Cycles

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Abstract

Standard macroeconomic models that assume an exogenous stochastic process for multifactor productivity offer the interpretation that recessions are the result of "bad news" (technological regress) and expansions are the result of "good news" (technological advancement). The view taken here is that both expansions and recessions are the result of "good news" in the sense that in both cases, aggregate production possibilities have increased. Recessions can be thought of as the transition from one technological frontier to the next.

1 Introduction

Standard neoclassical models of economic fluctuations often rely on an exogenous autoregressive process for multifactor productivity. The interpretation is that recessions are the result of a temporary decline in productivity while expansions are the result of a temporary increase in productivity. In other words, downturns are the result of 'bad' news and expansions are the result of 'good' news. The view taken here is that neither recessions nor expansions are necessarily good or bad news, and that both are, in fact, associated with increasing production possibilities. The driving force behind an economy's development lies its ability to produce newer, more productive capital goods. However, when a new, more productive capital good is introduced into an economy, it takes time to learn how to use it appropriately and to improve on its operation and efficiency. Therefore, there will be a natural slowdown as the economy transitions to the new "technological frontier". Once the economy has sufficient knowledge of the new product, it begins to improve on it - producing the next generation. However, as each new generation is introduced, the marginal productivity gains become smaller and smaller. Eventually, the marginal gains will become small enough that the costs outweigh the benefits of improvement. At that point, when a capital good is "played out", a new, revolutionary product must be developed - and the cycle starts over.

For example, Gordon (2000) uses the example of word processing. The invention of the typewriter surely represented a dramatic increase in productivity once individuals learned how to type. The next generation memory typewriter, which eliminated much repetitive retyping, also marked a substantial productivity gain. However, as we move through successive improvements (a DOS PC with Wordperfect 4.2, Wordperfect 6.0, Word for Windows, Word 95, Word 98, Word

2000), one can imagine the marginal productivity improvements rapidly approaching zero. From my own experience, I can say that I am no more productive using windows 98 than I am using windows 95. However, as we speak, Microsoft is working on perfecting word processing software with voice recognition - possibly the next "revolution" in word processing software. From a more historical context, Gordon (2000) examines multifactor productivity from 1870 - 1999. He finds that they show a growth pattern of "slow - fast - slow- fast".

<i>Period</i>	1870 – 1913	1913 – 1972	1972 – 1995	1995 – 1999
<i>MFP</i> (% Δ)	.47	1.08	.02	1.25

Gordon attributes this pattern to patterns of innovation. The Late 1800's produced many revolutionary inventions. For example, the electric light (1879), the internal combustion engine (1877), the telephone (1876). Gordon attributes the fast growth 1913 - 1972 to such inventions as listed above. While it is difficult to distinctly classify inventions by generations, one might suggest that the first generation electric light led to future generations such as the power station, electric train, radios, and air conditioning. Similarly, the internal combustion engine led to future generations such as automobiles, airplanes etc.

Similarly, the rapid expansion of the late 90's could be attributed to the invention of the microprocessor (first marketed by INTEL in 1971). As a first generation invention, the microchip has led to future generation products such as pentium processors, cellular telecommunications, and the world wide web. The relative length of the "slowdowns" compared the expansions should depend on two factors: (1) The difficulty involved in perfecting and learning the new

technology and (2) the pace at which the new product diffuses through the economy. A new product which is difficult to learn and costly to adopt will be associated with a large period of low productivity and a corresponding long, slow recovery. On the other hand, a product that is easy to learn and rather costless to adopt will be associated with a very short contraction and a quick recovery.

Andolfatto and Macdonald use a model of technological adoption to examine the U.S. from 1940 to the present. They discover that the period is represented well by the production and adoption of five new technologies. The first was developed in the late forties, was easy to learn, diffused rapidly, and quickly developed into widespread usage (over 70%). In the mid fifties, a new product came out that was also easy to use, but was a small improvement and, hence, while it diffused rapidly, it never reached more than a 40% acceptance rate. More recently, another innovation began in the early seventies (while the authors don't identify these innovations as particular products, it is reasonable to believe that this one is computer related). Unlike previous technologies, this one was more difficult to learn and more difficult to adopt. However, eventually (by the mid eighties), it reached a 60% adoption rate. Their model, however, took the size of technological advance as exogenous. This paper plans to endogenize that variable.

Authors such as Greenwood and Jovanovic (2000) and Boldrin and Levine (2001) offer further evidence of this type of growth cycle by looking at the stock market. Boldrin and Levine note that the stock market tends to rise slowly, but drop very rapidly with periodic crashes. While many suggest that this market behavior is the result of bubbles, asymmetric technology shocks, etc., Boldrin/Levine argue that this market behavior is the natural result of innovation cycles. The market rises during periods in which an existing technology is being improved on. Note

that this is a period of very little uncertainty. However, eventually, the market learns that the existing technology is "played out". At that point, there is a great deal of uncertainty as to how the new technology will evolve, how difficult the diffusion process will take, etc. - the market responds with a sharp downturn until this uncertainty is resolved (ie, a slow recovery). Greenwood and Jovanovic use this type of explanation to explain the behavior of the stock market during the 1970's. In 1970, the ratio of market capitalization to GDP was approximately 1. In 1973, that ration dropped dramatically to approximately .4 and stayed at .4 until the late eighties. The current ratio is currently around 2. Greenwood/Jovanivic attribute this to the development of the microchip in 1971. The market recognized the complexity and difficulty involved in computerization and adjusted prices accordingly.

There is an important lesson to be learned from the above examples. Economic slowdowns need not be caused by bad news. The introduction of the computer chip, while taking place during a period of sluggish (even negative) economic growth, represented an increase, not a decrease in the productive cababilities of the U.S.. The measured drop in MFP is simply represents the learning processas the economy transitions from old to new technology.

This paper formalizes the ideas discussed above by developing a general equilibrium model of technology creation. The model is along the lines of Boldrin and Levine (2001). However, in Boldrin and Levine, the decisions concerning the timing of new product develoment, upgrading and reproducing existing capital are determined primarily by parameter values and technological restrictions. Here, those decisions will be determined endogenously. A technology sector expends resources to produce new technologies. Periodically, the technology sector will develop a "revolutionary product", but most of the time, it simply improves on existing technologies. The

decision to "revolutionize" will depend on the shape of the learning curve of the new technology. Eventually, it will be the case that upgrading existing technologies will not be worth the effort required. At that point, resources will be moved into the development of new technologies. When new technologies are developed, the manufacturing sector automatically (and costlessly) adopts them.

2 The Model

2.1 The Capital Goods Sector

The capital goods sector of the economy uses the existing stock of capital goods to produce new capital goods to be used by the production sector. It also uses the knowledge embodied in capital goods to improve on existing capital goods. Specifically, capital in the economy be indexed by i and j where i represents the type of capital and j represents the generation of capital. For example, suppose that we consider communications equipment to be a type of capital good. Then, generation 1 might represent the telegraph, while generation 5 might be the cellular telephone. Assume that the representative firm in the technology sector has 1 unit of type i , generation j capital, or k_{ij} . The production possibilities for t are

1. Investment: Each unit of k_{ij} produces $A \succ 1$ units of the same type and generation of capital (type i , generation j)
2. Upgrading: Each unit of k_{ij+1} produces $\left(\frac{\Phi}{1+\omega_j}\right) L$ units of the next generation capital type i , generation $j + 1$

The capital goods sector will be restricted to only undertake one activity at a time. This shouldn't qualitatively change the results and will allow the analysis to go through without the need for tracking the distribution of capital across sectors. Further, diminishing returns to labor are excluded to avoid the necessity of tracking the distribution of labor across sectors.

The intuition here is straightforward. The reproducing of existing capital goods is a simple, automated task. Note that it will be possible for the economy to maintain a constant long run rate of growth through this process. If no new capital are created and no upgrading takes place, the model is a simple AK economy. Upgrading is a more complicated task which requires the addition of skilled labor as well as capital. Most importantly, upgrading exhibits diminishing returns. The idea here is that each upgrade will produce small and smaller increases in productivity. The parameter ω is meant to capture the size of these diminishing returns. For example, when Microsoft released its first word processing software program (think of this as the first generation of a new capital good), the improvement in productivity over, say, electric typewriters (the latest generation of the previous type of capital) was sizeable. However, as Microsoft proceeded through Word, Word95, Word98, etc., the productivity gains from each new edition become smaller and smaller. This is the key to the entire model. An economy cannot grow indefinitely from improving on existing capital. Eventually, it must either settle with simply increasing the stock of capital or it must begin searching for new, novel ideas. Sticking with the Microsoft example, as the improvement opportunities diminished with traditional word processing software, Microsoft began shifting resources towards things like voice recognition software (think of voice recognition as the next type of capital).

2.2 The Research Sector

The research sector of the economy develops the blueprints for new capital goods and builds the prototype. When new types of capital goods are produced, they are initially unproductive relative to state of the art versions of earlier types. This can be thought of two ways. First, early generations of capital are "prototypes", or "betas". They are not very productive due to minor flaws or "bugs" in the design. They must be tested and redesigned before they will be used to produce consumption goods. Second, new capital have a "learning by doing" component. Initially, workers must learn how to use a new type of capital. As they redesign it, they become more familiar and, hence, more productive. As with investment, R&D production is linear. Further, it is assumed that only labor is used in the research sector. This assumption is not necessary, but allows for easier calculation. All that is necessary is for the process of upgrading to be less labor intensive than R&D, but more labor intensive than Investment. First, a plan for new capital must be developed. Each unit of labor applied to research can produce some fraction B of the completed blueprint. Let ϕ represent the cumulative research, then

$$\phi' = \phi + B\tilde{L} \tag{1}$$

Note that it will require at least $(1/B)$ periods to complete a new research plan (total labor supply in the economy is set to 1). Once a plan is completed ($\phi = 1$), any capital of type i , generation j can be converted to type $i + 1$, generation 0 on a one for one basis.

2.3 The Production Sector

The Production sector of the economy converts type i , generation j capital into consumption using the following technology. It should be noted here that consumption here is not measured in physical units, but rather in quality units. That is, over time, we can produce more consumption as well as better quality consumption.

$$c = \gamma^{i+j} k_{ij} \tag{2}$$

Note that there are three potential sources of growth in this economy. First is growth due to an increase in the stock of physical capital. The second source is due the continual upgrading of the existing capital stock and the periodic development of new, more productive capital goods. However, upgrading capital will not represent a long run (sustainable) source of growth due to diminishing returns to upgrading.

2.4 Consumers

Consumers have preferences defined over streams of consumption represented by the expected utility function. Again, for simplicity, labor will be supplied exogenously at 1 unit.

$$\sum_{t=0}^{\infty} \beta^t W(c_t) \tag{3}$$

$$W(c) = -\frac{1}{\theta}c^{-\theta}$$

where c represents consumption and $\beta \prec 1$ is the discount rate.

3 Analysis

To begin, we need to place some initial restrictions on some of the parameters of the model to avoid some uninteresting results. Suppose that there exists 1 unit of type zero, generation zero capital. There are two options available to produce consumption to be available for the next period. First, we could simply build more of the type zero, generation zero capital (we could produce A units). This would provide us with A units of consumption ($\gamma^{0+0}A$). The second choice is to upgrade our capital to type zero, generation one. Using this method yields at most Φ units of capital next period (assuming that all available labor is dedicated to upgrading rather than innovating) which can be used to produce $\gamma\Phi$ units of consumption next period. We want to be sure that there is always some range for which upgrading is a preferable option to simply reproducing existing capital. Otherwise the model collapses into a standard AK framework with exogenous growth rate A . Therefore, it must be the case that

$$\gamma\Phi \succ A \tag{4}$$

Secondly, we know that labor will be attracted to the activity with the highest wage (i.e

the highest marginal product of labor). Once again, we have to be sure that there exists a range of parameter values for which the marginal product of labor in the capital goods sector (specifically, the marginal product of labor in upgrading) is greater than the marginal product of labor in research. Again, assume that we are starting with 1 unit of type zero, generation zero capital. One unit of labor used in upgrading will generate Φ units of type zero generation one capital. On the other hand, each unit of labor dedicated to research produces B units of a blueprint for type 1, generation zero capital. Note that the lifetime value of type one capital is γ times that of type zero capital. Therefore, it must be the case that

$$\Phi \succ \gamma B \tag{5}$$

to be sure that there exists a labor allocation with a positive amount of labor engaged in upgrading. Otherwise the model would once again reduce down to an AK model (with an average growth rate of γA).

Given the above parameter restrictions, the model will revolve between three distinct regimes. While the current type of capital is quite new, the costs of upgrading are small relative to the benefits. Therefore, early on, all the economy's resources not devoted to consumption will be used upgrading the economy's capital stock. In this region, growth is a consequence of technology accumulation as well as physical capital accumulation. Eventually, the current technology will "play out". That is, the costs of upgrading will drop below the benefits. This will result in the labor force shifting from upgrading into research and the capital stock shifting out of upgrading and into traditional investment. Growth in this region slows because technology accumulation

stops temporarily (actually, technology accumulation is still taking place but hasn't manifested in increased productive capability yet). To determine the upper bound for upgrading, set the marginal product of capital in investment equal to the marginal product of capital in upgrading. Note that the marginal product in upgrading must be scaled up by the factor γ because new generations of capital produce more consumption than older generations.

$$\begin{aligned} A &= \frac{\gamma\Phi}{1 + \omega j^*} \\ j^* &= \left(\frac{1}{\omega}\right) \left(\frac{\gamma\Phi}{A} - 1\right) \end{aligned} \tag{6}$$

This solution makes sense. The "technological frontier" is inversely related to ω . Recall that this parameter governs the degree to which diminishing returns result with each upgrade. The term $\frac{\gamma\Phi}{A}$ represents the baseline productivity in upgrading relative to investing. The above parameter restriction guarantees that this is bigger than one.

The length of the second phase - one in which physical capital simply reproduces itself is determined through the parameter value for B . A completed plan takes $\left(\frac{1}{B}\right)$ periods. Once the plan is completed, some of the economy's capital will be converted into the new type of capital. Note that new capital is initially quite unproductive relative to the existing capital (existing capital is generation j^* while the new type will begin at generation 0). The new type, however, has a very steep learning curve and can be upgraded so that eventually it will be more productive than the existing stock. Suppose that type one capital has just been invented. You have one unit of type zero, generation j^* capital at your disposal. You have two options for producing consumption at some future time period M^* . First, you could simply reproduce your

existing capital for $(M^* - 1)$ periods and then convert that capital into consumption. That would provide A^{M^*-1} units of consumption. The second option would be to convert your capital into type one in the current period, upgrade that capital for $M^* - 2$ periods, and then convert the resulting capital into consumption. This would result in

$$\gamma^{M^*-2} \left[\prod_{i=0}^{M^*-2} \left(\frac{\Phi}{1 + \omega i} \right) \right] \quad (7)$$

units of capital in time M^* . Setting the two equal will allow us to solve for M^* . Note that M^* will dictate the point at the new type of capital becomes useful for producing current consumption. Hence any of the old type of capital should be used up at M^* . At this point, the cycle starts anew.

3.0.1 Stage 1: Upgrading

The economy initially begins with an initial stock of capital. For simplicity, assume that the initial stock is 1 unit of type 0, generation 0 capital (k_{00}). For periods 1 through j^* the capital stock is upgraded to the next generation every period. Labor is entirely devoted to upgrading the capital stock. The economy grows at the rate of capital accumulation plus technology growth. The first order condition governing consumption give us optimal consumption growth.

$$\begin{aligned} \beta \left(\frac{c_i}{c_{i+1}} \right)^{\theta+1} &= \left(\frac{\gamma^i \Phi}{1 + \omega i} \right)^{-1} \\ \frac{c_{i+1}}{c_i} &= \left(\frac{\gamma^i \Phi}{1 + \omega i} \right)^{\frac{1}{1+\theta}} \end{aligned} \quad (8)$$

Note that during this phase, capital becomes more productive, but also becomes more expensive. Initially, the stock of physical capital grows, but eventually, begins to shrink. In fact, at j^* we know the growth of potential output through investment ($g_k = A$) is equal to the growth of potential output through upgrades ($g_\gamma + g_k$).

3.0.2 Stage 2: Research

At j^* the rising cost of new capital finally outpaces productivity and the process of upgrading stops. Labor is shifted into research and capital is shifted into investment. During this period, the capital stock grows at the exogenous rate A . From the first order condition for consumption, we know that consumption grows at the rate

$$\frac{c_{t+1}}{c_t} = (A\beta)^{\frac{1}{1+\theta}} \quad (9)$$

The length of the research stage is determined by the exogenous parameter B .

3.0.3 Stage 3: Development

At time $j^* + B$ the blueprint for a new type of capital becomes available. At this point, some of the capital stock will be reproduced and used for current consumption while the remaining capital stock is converted to the new type and then upgraded until it is useful for producing consumption goods. Therefore, the period $j^* + B$ budget constraint is given by

$$k_{ij} = c + A^{-1}k'_{ij} + k_{i+1,0} \quad (10)$$

During the economy's "development" phase, the capital used for consumption grows at an exogenous rate of A . Therefore, condition consumption consumption grows at rate

$$\frac{c_{t+1}}{c_t} = (A\beta)^{\frac{1}{1+\theta}} \quad (11)$$

New capital in the economy grows at the rate $\left(\frac{\gamma\Phi}{1+\omega_j}\right) = g_k$.

Old capital can be used for either consumption or investment. Therefore, the period by period budget constraint for the periods $j^* + B \leq t \leq j^* + B + M^*$ is given by

$$k_t = c_{t+1} + A^{-1}k_{t+1} \quad (12)$$

Finally, note that any optimal plan will use up the old type capital once the new capital is ready for consumption purposes ($k_{ij}^{M^*} = 0$).

To solve the model, first note that we have a starting capital stock (of type 0 generation 0) equal to one which is allocated towards consumption and upgrading.

$$k_{00} = 1 = c + \left(\frac{\Phi}{1 + \omega i} \right)^{-1} k_{01}$$

At time j^* the process of investment begins. The period j^* budget constraint is equal to

$$k_{0j^*} = 1 = c + (A)^{-1} k'_{0j^*}$$

At period $j^* + B$, the new capital becomes budget constraint is given by

$$k_{ij} = c + A^{-1} k'_{ij} + k_{i+1,0} \tag{13}$$

Lastly, we have the terminal condition that the old style capital is completely used up at the time that the new style capital is productive enough to produce consumption. ($k_{ij^*}^{M^*} = 0$). Solving the budget constraints forward and inserting the starting and terminal condition results in the lifetime budget constraint. Next, at time $j^* + B$ (when the plans for the new type of capital become available) resources allocated towards new capital creation must provide equal lifetime utility at the margin as resources allocated towards consumption. Let V_{00} denote the lifetime value of one unit of type 0 generation 0 capital. The value of k_{ij} unit of type i generation j capital will produce $(\gamma^{i+j} k_{ij})^{-\theta} V_{00}$ units of welfare. Therefore, the optimality condition governing new capital formation can be written as

$$\beta (c)^{-(1+\theta)} = \beta^{M^*+1} \left[\gamma^{M^*} \prod_{i=1}^{M^*} \left(\frac{\Phi}{1 + \omega_i} \right) k_{10} \right]^{-\theta} V_{00} \quad (14)$$

Finally, we have the bellman equation defining the value function.

$$V_{00} = \sum_{i=1}^{j^*+B+M^*} \beta^i U(c_i) + \beta^{j^*+B+M^*+1} \left[\gamma^{M^*+1} \prod_{i=1}^{M^*} \left(\frac{\Phi}{1 + \omega_i} \right) k_{10} \right]^{-\theta} V_{00} \quad (15)$$

Equations (14), (15), and the lifetime budget constraint define a solution for k_{10} , c , and V_{00} .

Choosing parameter values is the next step.

β (Rate of Time Preference)	.96
A (Productivity in Investment)	1.03
γ (Rate of Growth in Technology)	1.05
Φ (Baseline productivity in Upgrading)	1.06
B (Productivity in Research)	.2
ω (Degree of Diminishing returns in upgrading)	.007
θ (Intertemporal Elasticity of Substitution in Consumption)	-.4

Given the above parameters, the economy has a long run rate of growth equal to 5% per year.

However, the economy actually averages 4% annual growth by moving back and forth between the low growth state (research and development) and the high growth state (upgrading). Given the parameters, the maximum growth of consumption is

$$\frac{c_{i+1}}{c_i} = (\gamma\Phi)^{\frac{1}{1+\theta}} = 1.19$$

However, this growth rate continually declines. The first switching point j^* is equal to 12 (capital reaches twelve generations before upgrading becomes too expensive. At j^* (and until $j^* + B + M^*$), growth of the economy is dictated by the growth of physical capital through investment. During this period, we get a growth of consumption equal to

$$\frac{c_{t+1}}{c_t} = (A\beta)^{\frac{1}{1+\theta}} = .98$$

So consumption shrinks during the "recession". The length of this contraction is determined by the exogenous parameter B . (In this case, the research phase takes 5 periods) and M^* (in this case, M^* is determined to be 5). Therefore, the economy experiences alternating expansions (of length equal to 12 periods) where consumption grows at an average rate of 8.5% and recessions (of length equal to 10 periods) where consumption contracts at a rate of 2%. Figures (1) – (4) plot the transitions for new capital, the aggregate capital stock, consumption, and productivity (units of new capital per unit of old capital).

4 Conclusions

Standard macroeconomic models stress the fact that expansions and contractions are the result of random fluctuations to productivity. Expansions are the result of "good" news while recessions

are the result of "bad" news. The view taken here is that both recessions and expansions are both the result of the development of new technologies.

When new technologies are invented, they are initially very unproductive. However, over time, they are modified and improved upon. Each successive generation becomes more productive at producing consumption goods, but becomes more costly to update. For example, the telegraph was a new type of capital used in the production of communication services, then successive generations would be the telephone, cordless phone, cellular phones, etc.. The constant pattern of research, invention, development and replacement create a natural cycle of economic activity.

- When a new type of capital is in its early stages, the cost up upgrading is low relative to the productivity gains. Consumption grows at above trend rates as the capital stock is constantly upgraded. However, as upgrades become more and more expensive, more capital is devoted to development rather than consumption. Eventually, a technology becomes "played out" in the sense that it is no longer cost effective to continue updating. Consumption growth falls and labor is reallocated to research activities (i.e., the invention of new types of capital). Note that the length of this expansionary period depends on the degree of decreasing returns to upgrading (ω).
- Consumption growth remains low during the research period. Capital is simply reproduced rather than upgraded. Labor is devoted to reserach activities. Eventually, a new type of capital is discovered (discovery time is treated as exogenous in this framework). However, the new capiatl is still unproductive relative to the existing capital stock. A development phase must take place before the new capital can be used for consumption purposes. Note

that while new capital is being improved, the old capital is in the process of being used up in anticipation of the new capital coming online. Therefore, the aggregate capital stock falls. This period looks very much like a recession - a declining capital stock and low consumption growth - but actually, lifetime consumption possibilities have actually increased. The length of the development also hinges crucially on the curvature of the upgrading process (ω) and well as the baseline level of productivity (Φ). Once the new type of capital is productive enough to produce consumption goods, the cycle begins anew.

Obviously, there are some important drawbacks in the current framework. With only one production sector, there is no possibility of simultaneously operating multiple technologies - each in a different developmental stage. Further, the research stage should ideally be treated as endogenous with a tradeoff between research time and certain features of the new capital (i.e. initial productivity or developmental path). These are questions to be looked at in future research.

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Figure 1:Capital

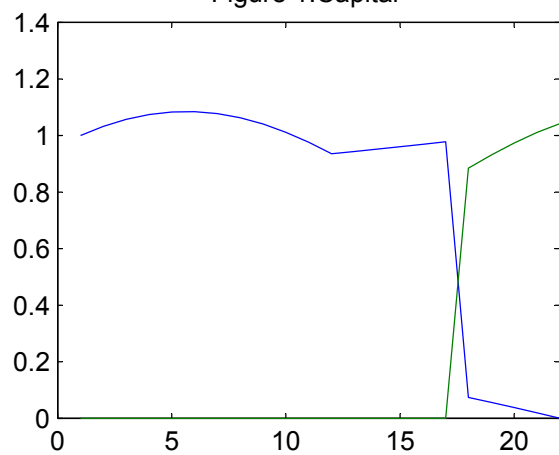


Figure 2:Capital stock

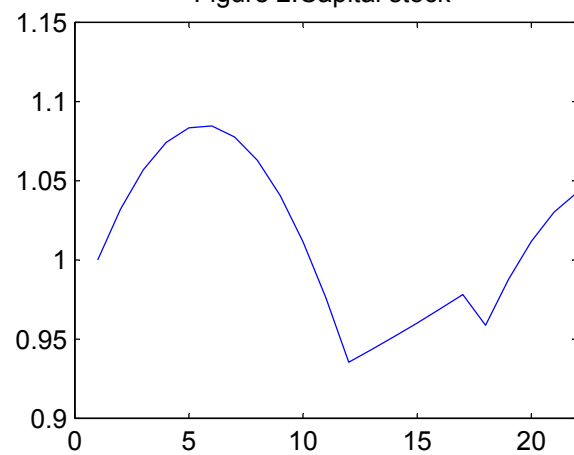


Figure 3:Consumption

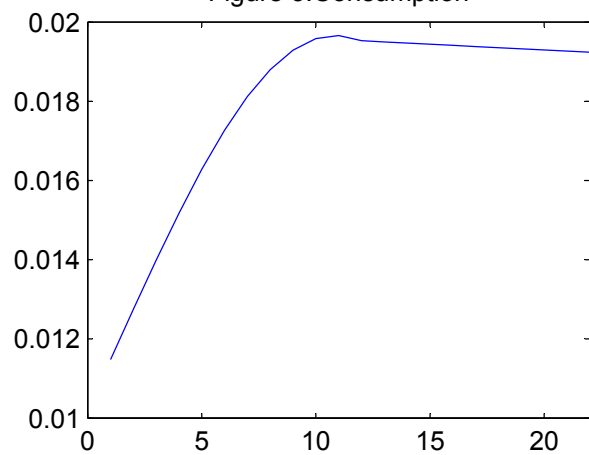


Figure 4:Productivity

