Technology Policy, Demand-Driven Innovation and Inequality*

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Abstract

We provide a new explanation for the origin and the *direction* of technical change and we analyze its role in the changes of the US wage structure that occured in recent decades. We show that the US technology policy had a relevant role in stimulating the wave of innovation that hit the US economy in the 1980's and 1990's. Beginning in 1980 technology policy shifted rapidly from a first priority on Cold War security to a first priority on economic competitiveness. We provide a description and an evaluation of the new tools of technology policy introduced to face international competitiveness. More precisely we discuss both components of this new strategy, namely, *r&d cost-reducing* policies and *maket-size* policies. Then, using a quality-ladders growth model we focus on a market-size policy mechanism and we show that government's stimulus to high-tech sectors, via demand pull, increases innovation and the wage of skilled workers. Anecdotal evidence and the model's calibration results support our theoretical findings.

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1 Introduction

In a recent survey Daron Acemoglu (2002), summarizing the expanding literature on the role of technological change in explaining wage inequality in the US, distinguishes between exogenous and endogenous theories. More precisely he distinguishes between theories that consider the skill-bias of new technologies as exogenously given and theories that offer an explanation for the bias of technical change. The first group of theories argues that there has been a "technological revolution" beginning in the 1970's or 1980's which led to more rapid skill-biased technical change. These theories treat technological change as an exogenous shock and explain the skill-bias with the hypothesis that new technologies are more complementary to skilled workers[1]. The second group of theories, rather than assuming an exogenous technological revolution, seeks for an explanation of the bias of technical change in market mechanisms (see Acemoglu 1998 and Kiley1999). The basic idea is that innovation is driven by profitability and that a key determinant of profitability is *market size*. An increase in the market size, conceived as an increase in the supply of skilled workers, encourages the development of technologies that use the more abundant factor[2]. More specifically, the Vietnam War draft and the high college enrollment rate of the baby boom cohorts increased the supply of skilled workers, thereby inducing the development of skill-intensive technology (i.e. computers).

A different explanation of the factor bias of technical change is presented in Dinopoulos and Segerstrom (1999). This paper has in common with the endogenous theories discussed above the idea that innovation are profit-driven, but both the primary cause that triggers innovation and the economic transmission mechanism are different. They show that trade liberalization increased the market demand for world leading firms (technological leaders). This increased the monopoly rent of being a market leader, thus stimulating investment in innovation. Supposing that innovative firms are on average skill-intensive they reach the conclusion that trade liberalization is at the root of the increase in the skill premium.

In our model, as in Dinopoulos and Segerstrom (1999), the incentive to innovate is driven by the monopoly rent of being a technological leader, but we introduce a more complex market structure and propose a new explanation for the primary force behind technical change.

In the first place, we suggest that technology policy has been a primary force that contributed to the recent wave of technological innovation in the US. Beginning in 1980 we observe a switch in the main target of the US technology policy from a first priority on Cold War security to a first priority on international economic competitiveness. The change was triggered by the eclipse of the Soviet's military power as a

[1] See Acemoglu (2002) p.29-33 for references and a more complete presentation.

[2] Nathan Rosenberg (1994) had already used a similar hypothesis to explain the historical roots of the US technological leadership.

treat to US security (first symbolized by the easing of tension during Gorbachev's administration), and by the contemporaneous recovery of the European and Japanese economies from the war.

The erosion of the US leadership in high-tech sectors escalated in the late 1970's and 1980's and policy makers had to find new policy tools to deal with this new threat. On one hand we find, in the 1980's and 1990's, the introduction of new technology policy tools to stimulate firms' incentive to invest in innovation. Fiscal incentives for R&D, the stenghtening of intellectual protection, the incentive to collaboration between federal laboratories and firms and the relaxation of antitrust persecutions of research joint ventures were all targeted at reducing the cost of innovation for firms. On the other hand, in the same period, we observe a dramatic increase in government investment in the new key high-tech sectors (for instance, investment in equipment and software, which was 20 percent of total government investment in 1980, climbs to about 40 percent in 1990 and to more than 50 percent in 2001). The effect of this kind of policy does not consist in reducing innovation costs but in increasing the *market size* for high-tech goods -thus stimulating firms to become technological leaders.

In our model the high-tech sectors are those where innovation brings technological improvements higher than the average. For simplicity we suppose that all manufacturing firms use only unskilled labor and all r&d firms use only skilled labor. When the government increases spending in high-tech sectors by one dollar and decreases spending in the low-tech sectors by the same amount the overall effect on profits is positive. Intuitively, thanks to the stronger innovation capacity of high-tech sectors, the increase in profits in these sectors more than compensate the decrease in profits in low-tech sectors. Moreover, the increase in total profits will trigger, via arbitrage condition, an increase in the demand of r&d workers (skilled workers) and in their wage. In our vision, a realistic economic interpretation of the effects of this policy lead to think of it as triggering an increase in the demand not only of r&d workers but also of any worker with intellectual skills. It is commonly accepted that this type of workers are more intensively used in highly competitive technologically advanced firms (e.g. financial legal consulting services, management services, marketing services, ICT adoption experts, etc.). Following to this view,the policy mechanism at work in our stylized economy can be understood as a force able to influence the demand of skill workers and not only its relatively important subset of r&d workers (i.e. scientists and engineers).

We model only the effect of the market-size-increasing technology policy but we also suggests possible extensions to include the effects of r&d *costs-reducing* policies. Moreover, although we use a closed economy model, the change in technology policy that we analyze is triggered by the increase in international competition and this creates an indirect link between international trade and inequality -in line with the intuition we find in Dinopoulos and Segerstrom (1999).

We use a R&D-driven growth model with intra-industry vertical innovations (see Grossman and Helpman 1991) and human capital accumulation (see Dinopoulos and Segerstrom 1999) with the following original features:

a) *Asymmetric Sectors*: there are an continuum of sectors, each one with a different innovation power

(innovation produces different product quality jumps)

b) *Asymmetric Public Policy*: the government can allocate its expenditure in manufactured goods using a continuity of different policy rules, from the extreme symmetric rule (each sector gets the same), to the extreme asymmetric rule (the sector with the highest quality jump gets the highest spending).

The main result of the model is that when the government moves from a symmetric spending to a policy that promotes more sectors with high quality jumps (high-tech sectors) there is an increase in the relative supply of skilled workers and an increase in the skill premium. Furthermore, we show that when the government follows an asymmetric spending rule, increases in the level of per-capita public spending, at a constant composition, will have a positive effect on the skill-premium.

The paper is organized as follows. Section 2 presents a brief discussion of the evolution of the US technology policy after WWII and assembles anecdotal evidence for our argument. Section 3 sets up the model. Section 4 and 5 derives the main results and explains the intuitions for the macroeconomic consequences of the asymmetric steady states. In section 6 we calibrate the parameters of the model and then we simulate its trajectories, comparing the model's results to the actual skill premium data. Section 7 concludes.

2 Technology Policy and Wages: Facts and Numbers

In the decades that followed WWII the United States attained the highest level of scientific and technological achievement. With the world's largest domestic market and with European countries still recovering from the war there was little foreign competition for the defense-based high-tech US industries. The priority for policy makers was thus to meet the security threat coming from the Soviet Union. From the late 1940's until the mid-1960's we observe massive public investments in defense R&D and spectacular answers to Soviet's technological advances, such as the American moon landing, a response to the Soviet's launch of the Sputnik. Federal r&d funds were primarily directed to serve defense targets and, even if they turned out to have important spin-offs and have served sometimes as a de facto support to commercial technology, were not primarily targeted to contribute to the nation's economic competitiveness.

Technology policy during the Cold War consisted basically of funding for basic research on the one hand and funding for applied research and development related to federal defense projects on the other. As suggested by Lewis Branscomb and Richard Florida, the assumption that these activities would also sustain economic competitiveness was derived from a *supply-side* picture of how the commercial innovation mechanism would work. On one hand, there was a consensus on the so called "pipeline model" which conceives commercial innovations as spurring from scientific research automatically. The idea was that once government had provided basic research, product development and production would follow immediately thanks the market mechanism. In addition, as a complement to the pipeline model, policy makers assumed that technology created in pursuit of governmental missions, especially defense, space and nuclear energy, would transfer to industry automatically and at no cost. This is the "spin-off" hypothesis that together with the pipeline model formed the basic framework of the US technology policy during the Cold War, also known as the "Linear model" (see Banscomb and Florida 1998 p.16).

This vision of the innovation process allowed policy makers to hit the primary target of the Soviet's security threat (through funds for defense research and mission-oriented development) and to have the "positive esternality" of stimulating industrial innovation through the pipeline-spin-off mechanism. Hence, for policy makers the linear model had the attractive feature of achieving economic innovation goals without interfering with the autonomy of private firms -government did not have to "pick winners and losers".

While this model of science and technology policy was successful in containing Soviet expansionism, in the late 1960's there were early indications, as Japan and Germany recovered from the war, that defense-based policies were not working equally well in promoting economic security. In 1968, Michael Boretzky, a commerce department economic analyst, was the first to sound the alarm reporting the visible erosion of the balance of trade in high technology sectors (see Branscomb 1993). Nixon's Secretary of Commerce Maurice Stans made a strong case to Congress to reverse this high-tech competitiveness trend[3]. During his last year of office president Carter commissioned a study to discover new ways in which the federal government could enhance innovation rates in the private sector (see Branscomb 1998). Finally President Regan transformed these concerns into concrete action by declaring an administration competitiveness strategy (see Clark and Lan 1995). Therefore, in Branscomb words, "government's concern with ensuring a competitive commercial economy against technologically sophisticated competition from abroad began to provoke policy responses long before the fall of the Berlin Wall in 1989" (Banscomb and Florida 1998, p.15).

Before analyzing US government's response to foreign competition threat and how it radically changed the principles and the structure of technology policy, we want to give an idea of the magnitude of the problem. The erosion of the US leadership in high-tech sectors escalated in the late 1970's and 1980's. Between 1980 and 1991 the global market shares of the United States in the high-tech markets declined by 16 percent, while Japan's share increased by about 30 percent[4]. Guerrieri and Milana (1991) using a different classification scheme for high-tech sectors (different form the OECD scheme) found that Japan's share of high-tech export doubled from about 7 percent in 1970-73 to about 16 percent in 1988-89, while the US share declined from 30 percent to about 21 percent. They also show that the revealed comparative

[3] "If we are to maintain our advantages in this area we must first of all accept the idea that it has became a proper sphere of governmental action". Maurice Stans, Hearing of the House of Representatives Committee on Science and Astronautics on "Science, Technology and the Economy" (Washington, D. C. US Goverment Printing Office, July 27-29, 1971), p.17; quoted in Harvey Brooks (1972)

[4] See NSF (1998), appendix table 6-5.

advantage of the United States in high–tech products -measured by the ratio between the US share of global export of these products and the US share of global export of all manufactured products- declined between 1970 and 1989 . Moreover, the US lost of comparative advantage was concentrated in four major high-tech sectors: electronics, aircraft and parts, scientific instruments, and medical equipment. The erosion of the American position was especially pronounced in electronics, a sector where Japan and East Asian new industrialized countries scored dramatic gains; and in aircrafts and parts, where the competitiveness of European products increased radically (see Guerrieri Milana 1991, and Tyson 1992 table 2.4).

This evidence shows that the criticism voiced by Michael Boretsky in the 1960's was warranted. It shows the failure of the linear model and it suggests that the pipeline from science to innovation and the spin-off from military technology to business applications were neither automatic nor free. In analyzing the government's response to this situation we will see that the challenge of international competitiveness changed radically the framework of US technology policy.

The first response of the Congress to the rising concern about US high-tech competitiveness was to accelerate the spin-off of government technology to commercial sector. Below we list some the most relevant policy measures used to reach this goal.

1. The Bayh-Dole Patent Act (1980) allowed agencies to issue patents for inventions made with the agency funds.

2. The Stevenson-Wydler Technology Innovation Act (1980) required Federal Laboratories to facilitate the transfer of federally owned and originated technology to the private sector and to local and state governments.

3. The introduction of Research and Experimentation (R&E) Tax Credit (1981) created an incentive for firms to increase their spending in R&E.

4. The Small Business Innovation and Development Act (1982) established the Small Business Research (SBIR) program within the major Federal R&D agencies to increase government funding of research with commercialization potential within small, high-technology companies.

5. National Cooperative Research Act (1984) reduced the risk of civil antitrust prosecution of firms collaborating on generic precompetitive research.

6. The Federal Technology Transfer Act (1986) amended the Stevenson-Wydler Act to authorize co-operative research and development agreements (CRADA) between Federal laboratories and other entities, including state agencies.

7. The Omnibus Trade and Competitiveness Act (1998) established the Competitiveness Policy Council to develop recommendation for national strategies and specific policies to enhance industrial competitiveness.

This package of policies showed policymakers had finally accepted that competitiveness policy was a 'proper sphere' of governmental action, as Nixon Commerce Secretary Maurice Stans had argued almost twenty years before[5]. In the following years during Presidents Bush and Clinton administrations there were other Acts that were basically amendments and refinements of the ones listed above; the foundations of the new US technology policy had been already built in the 1980's.

We can observe the effects of this shift of technology policy to a first priority on economic competitiveness taking a look at some basic empirical evidence. In figure 1 we see the pattern of the R&D to GDP ratio by source of funds. We observe the post war military build up from 1950 to mid-1960's. A subsequent slowdown, lasting a decade, is often attributed to Vietnam-War-era skepticism about science and technology and to the recession of the early 1970's[6]. The Reagan military expansion that followed lasted until 1986; the advent of the new technology policy is reflected in the negative growth of federal R&D spending through the mid-1990's. The decomposition of federally funded R&D in defense and non defense shows that only the defense component faced radical cuts (see figure 2). The important fact to notice here is the dramatic increase of private R&D in the last two decades: between 1980 and 1990 the ratio to GDP increased by 30 percent (the level by 59 percent) and climbed to 70 percent in the period 1980-2000 (the level increased by 124 percent). Looking at this evidence it seems that the new technology policy has been hitting the target of stimulating industrial innovation.

Finally we want to talk about the role, in the new setting of the US technology policy, of a policy tool that has often been downplayed by economists and other analysts: *government procurement.* David Hart of the Kennedy School of Government presents the argument in an interesting way: "R&D spending was typically accompanied by other measures that deserve at least as much credit for technological payoffs. For instance, the Department of Defense (DOD) not only funded much of the physical science and engineering R&D that led to advances in semiconductors and computers, it also purchased a large fraction of products themselves, especially the most advanced products. The DOD guaranteed that a market for electronics would exist, inducing private investment on a scale that would not have otherwise followed even the most promising research results" (Hart 1998 p.1). This is a crucial point for the argument we make in our paper: government's policy not only stimulated private investment in innovation with the policy measures discussed above but, through procurement, *guaranteed a market* to innovative firms.

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[5] See footenote 3.

[6] In the late 1960's there was a broad movement of public opinion in the US who radically attacked the faith in science and technology. And even those who continued to have faith in scientific progress found more difficult to believe that the nation's problems could be solved through science. The Vietnam War was the symbol of the dilemma: a technological superpower hadn't been able to defeat a nation equipped with a nineteen century technology.(see Bruce Smith 1990 for a disussion of the slowdown in federal R&D during this period)

TABLE I

Growth rates of private and public investment in equipment & software

	1971-2002 (year avg.)	1971-1990 (year avg.)
private	0.18	0.09
public	0.16	0.16
Source: BEA, Nipa tables sections 5 and 7.		

Figure 4 shows that government investment in equipment and software - a sector in which high-tech industries have more weight than in the aggregate economy - increased dramatically in 1980's and 1990's. It is also notable that when we compare the growth rates of government and private investment in this sector we find that in 1971-1990 the yearly average growth rate of private investment is 9 percent while the growth rate of public investment is almost double, 16 percent (see Table 1). Moreover the fact that private investment catches up only in the 1990 shows that the first strong push toward the high-tech sectors, which represents the economy of the 21st century, came from the government. Our last piece of evidence, shown in Figure 5, confirms the idea that the composition of public spending shifted in the 1980's and 1990's towards the technologically more promising sectors.

The main finding of our paper is that the switch in the US technology policy, specifically the dramatic increase in public spending in high–tech sectors, stimulated investment and innovation in these sectors and boosted their demand for skilled workers (used intensively in these sectors) and their wages. By rising profitability in these sectors government increased the pay-off to be the technological leader, thus increasing the incentive for firms to hire r&d workers. In our vision, a realistic economic interpretation of the effects of this policy lead to think of it as triggering an increase in the demand not only of r&d workers but also of any worker with intellectual skills. It is commonly accepted that such skilled workers are more intensively used in highly competitive technologically advanced sectors (e.g. financial legal consulting services, management services, marketing services, ICT adoption experts, etc.) This is a very important remark because our goal is neither to link government spending to the dynamics of the wage of scientists and engineers, nor to explain inter-industry wage differentials, but to analyze the change in the overall US wage premium in the recent decades.

Unfortunately the only data available at the moment are the one showed in figure 4, there is no data for the complete pool of high-tech sectors included in the OECD definition (aircraft and spacecraft, pharmaceutical, computer and software, communication equipment). Thus a more complete dataset is needed to go beyond our anecdotal evidence and perform a more rigorous evaluation of the effects of public spending in high-tech sectors on the US wage structure. In section 6 we use the available data to calibrate the model, thus providing further empirical support to our argument.

3 The Model

3.1 Households

Households differ in their member's ability to become skilled workers; this ability, θ, is uniformly distributed over the unit interval. Household have identical intertemporally additively separable and unit elastic preferences for an infinite set of consumption goods indexed by $\omega \in [0,1]$, and each is endowed with a unit of labor/study time endowment whose supply generates no disutility. Households choose their optimal consumption bundle for each date by solving the following optimization problem:

$$\max \int_0^\infty N_0 e^{-(\rho-n)s} \log u_\theta(s) ds \tag{1}$$

subject to

$$\log u_\theta(s) \equiv \int_0^1 \log \left[\sum_{j=0}^{j^{\max}(\omega,s)} \lambda_\omega^j q_\theta(j,\omega,s) \right] d\omega$$

$$c_\theta(s) \equiv \int_0^1 \left[\sum_{j=0}^{j^{\max}(\omega,s)} p(j,\omega,s) q_\theta(j,\omega,s) \right] d\omega$$

$$W_\theta(0) + Z_\theta(0) - \int_0^\infty N_0 e^{-\int_0^s (r(\tau)-n)d\tau} T = \int_0^\infty N_0 e^{-\int_0^s (r(\tau)-n)d\tau} c_\theta(s) ds$$

where N_0 is the initial population and n is its constant growth rate, ρ is the common rate of time preference - with $\rho > n$ - and $r(s)$ is the market interest rate. $q_\theta(j,\omega,s)$ is the per-member flow of good $\omega \in [0,1]$ of quality $j \in \{0,1,2,...\}$ purchased by a household of ability $\theta \in (0,1)$ at time $s \geq 0$. $p(j,\omega,s)$ is the price of good ω of quality j at time s, $c_\theta(s)$ is nominal expenditure, and $W_\theta(0)$ and $Z_\theta(0)$ are human and non-human wealth levels. A new vintage of a good ω yields a quality equal to λ_ω times the quality of the previous vintage, with $\lambda_\omega > 1$. Different versions of the same good ω are regarded by consumers as perfect substitutes after adjusting for their quality ratios, and $j^{\max}(\omega,s)$ denotes the maximum quality in which the good ω is available at time s. As is common in quality ladders models I will assume price competition[7]

[7] All qualitative results maintain their validity under the opposite assumption of quantity competition.

at all dates, which implies that in equilibrium only the top quality product is produced and consumed in positive amounts. T is a per-capita lump-sum tax.

The instantaneous utility function has unitary elasticity of substitution and this implies that goods are perfect substitutes, once you account for quality. Thus, households maximize static utility by spreading their expenditures evenly across the product line and by purchasing in each line only the product with the lowest price per unit of quality, that is the product of quality $J = J^{\max}(\omega, s)$. Hence, the household's demand of each product is:

$$q_\theta(j,\omega,s) = \frac{c_\theta(s)}{p(j,\omega,s)} \quad \text{for } J = J^{\max}(\omega,s) \text{ and is zero otherwise} \tag{2}$$

The presence of a lump sum tax does not change the standard solution of the intertemporal maximization problem, which is:

$$\frac{\dot{c}_\theta}{c_\theta} = r(s) - \rho \tag{3}$$

Individuals are finitely lived members of infinitely lived households, being continuously born at rate β, and dying at rate δ, with $\beta - \delta = n > 0$; $D > 0$ denotes the exogenously given duration of their life[8]. People are altruistic in that they care about their household's total discounted utility according to the intertemporally additive functional shown in (1). They choose to train and become skilled, if at all, at the beginning of their lives, and the (positive) duration of their training period, during which the individual cannot work, has an exogenous duration $T < D$.

Hence an individual with ability θ decides to train if and only if:

$$\int_t^{t+D} e^{-\int_t^s r(\tau)} w_L(s)ds < \int_{t+Tr}^{t+D} e^{-\int_t^s r(\tau)} \max\left(\theta - \gamma, 0\right) w_H(s)ds,$$

with $0 < \gamma < 1/2$. The ability parameter is defined so that a person with ability $\theta > \gamma$ is able to accumulate skill (human capital) $\theta - \gamma$ after training, while a person with ability below this cutoff gains no human capital from training.

As Dinopoulos and Segerstrom (1999) we will focus on the steady state (balanced growth) analysis, in which all variables grow at constant rates and w_L, w_H, and c_θ are all constant. It easily follows that $r(s) = \rho$ at all dates, and that the individual will train if and only if her ability is higher than

$$\theta_0 = \left[\left(1 - e^{-\rho D}\right) / \left(e^{-\rho Tr} - e^{-\rho D}\right)\right] \frac{w_L}{w_H} + \gamma \equiv \sigma \frac{w_L}{w_H} + \gamma. \tag{4}$$

[8] As in Dinopoulos and Segerstrom (1999: 454) it is easy to show that the above parameters cannot be chosen independently, but that they must satisfy $\delta = \frac{n}{e^{nD}-1}$ and $\beta = \frac{ne^{nD}}{e^{nD}-1}$ in order for the number of births at time t to match the number of deaths at $t + D$.

The supply of unskilled labor at time t is

$$L(t) \equiv \theta_0 N(t) = \left(\sigma \frac{w_L}{w_H} + \gamma\right) N(t) \tag{5}$$

Following the same steps as Dinopoulos and Segerstrom (1999: 456) the reader can easily verify that the supply of skilled labor at time t is

$$H(t) = (\theta_0 + 1 - 2\gamma)(1 - \theta_0)\phi N(t)/2, \tag{6}$$

with $0 < \phi < 1$. Clearly in any steady state the growth rate of $L(t)$ and $H(t)$ is equal to n.

3.2 Manufacturing

Firms can hire unskilled workers to produce any consumption good $\omega \in [0,1]$ of the second best quality under a constant returns to scale (CRS) technology described by the simple unit cost function aw_L, with $a > 0$ common in all industries. However in each industry the top quality product can be manufactured only by the firm that has discovered it, whose rights are protected by a perfectly enforceable patent law. We will choose unskilled labor wage as the numeraire, that is: $w_L = 1$.

As usual in Schumpeterian models with vertical innovation (see e.g. Grossman and Helpman 1991 and Aghion and Howitt 1998) the next quality of a given good is invented by means of the R&D performed by challenger firms in order to earn monopoly profits that will be destroyed by the next innovator. During each temporary monopoly the patent holder can sell the product at prices higher than the unit cost. As Dinopoulos and Segerstrom (1999) we assume that the patent expires when further innovation occurs in the industry. Hence the monopolist rents are destroyed not only by obsolescence but also because a competitive fringe can copy the product using the same CRS technology.

The unit elastic demand structure[9] encourages the monopolist to set the highest possible price to maximize profits, but the existence of a competitive fringe sets a ceiling to it equal to the world lowest unit cost of the previous quality product. This allows us to conclude that the price $p\left(j^{\max}(\omega, s), \omega, s\right)$ of every top quality good is:

$$p\left(j^{\max}(\omega, s), \omega, s\right) = \lambda_\omega a, \text{ for all } \omega \in [0,1] \text{ and } s \geq 0. \tag{7}$$

Here we introduce the crucial feature of the model: the government sector specific per-capita spending $G_\omega(t) \geq 0$, for all $\omega \in [0,1]$ and $t \geq 0$. The Government uses tax revenues to finance public spending in different sectors and we assume that the government budget is balanced at every date: $N(t)T(t) = N(t)\int_0^1 G_\omega(t)d\omega$. Moreover we will assume $N(t)T(t) < \gamma N(t)/a$, i.e. $T(t) < \gamma/a$, in order to guarantee

[9] Any CES utility index with elasticity of substitution not greater than one would imply this result.

that public expenditure is feasible. Since we will be interested in steady states, in which per-capita variables are constant, from now on we will drop time indexes from per-capita taxation and per-capita public expenditure.

From the static consumer demand (2) we can immediately conclude that the demand for each product ω is:

$$\frac{N(t)\int_0^1 c_\theta d\theta}{\lambda_\omega a} + \frac{N(t)G_\omega}{\lambda_\omega a} \equiv \frac{cN(t)}{\lambda_\omega a} + \frac{N(t)G_\omega}{\lambda_\omega a} \equiv q_\omega, \tag{8}$$

where $c = \int_0^1 c_\theta d\theta$. In equilibrium this will coincide with the production of every consumption good by the firm that monopolizes it.

It follows that the stream of monopoly profits accruing to the monopolist which produces a state-of-the-art quality product will be equal to:

$$\pi(\omega, s) = q_\omega (\lambda_\omega - 1) a = (cN(t) + G_\omega N(t)) \left(1 - \frac{1}{\lambda_\omega}\right). \tag{9}$$

Hence a firm that produces good ω has an expected discounted value that satisfies

$$v(\omega, s) = \frac{\pi_\omega}{\rho + I(\omega, s) - \frac{\dot{v}(\omega,s)}{v(\omega,s)}} = \frac{q_\omega (\lambda_\omega - 1) a}{\rho + I(\omega, s) - \frac{\dot{v}(\omega,s)}{v(\omega,s)}},$$

where $I(\omega, s)$ denotes the worldwide Poisson arrival rate of an innovation that will destroy the monopolist's profits in industry ω.

In a steady state where per-capita variables all grow at the same rate, it is easy to prove that $\frac{\dot{v}(\omega,s)}{v(\omega,s)} = n$. Hence the previous equations become

$$v(\omega, s) = \frac{q_\omega (\lambda_\omega - 1) a}{\rho + I(\omega, s) - n}. \tag{10}$$

3.3 R&D Races

In each industry the leaders are challenged by the R&D firms that employ skilled workers and produce a probability intensity of inventing the next version of their products. The arrival rate of innovation in industry ω at time s is $I(\omega, s)$, and it is the aggregate summation of the Poisson arrival rate of innovation produced by all R&D firms targeting product ω.

Every R&D firm can produce a Poisson arrival rate of innovation in the product line it targets by use of a CRS technology characterized by unit cost function $bw_H X(\omega, s)$, with $b > 0$ common in all industries and $X(\omega, s) > 0$ measuring the degree of complexity in the invention of the next quality product in industry ω. Hence R&D is formally equivalent to buying a lottery ticket that confers to its owner the exclusive right to the corresponding innovation profits, with the aggregate rate of innovation proportional to the "number of tickets" purchased. The Poisson specification of the innovative process implies that the individual contribution to R&D by each skilled labor unit gives an independent (additive) contribution to the aggregate instantaneous probability of innovation: hence R&D productivity is the same if each research worker undertakes R&D by working alone as when she works with others in large firms.

The technological complexity index $X(\omega, s)$ has been introduced into endogenous growth theory after Charles Jones' (1995) empirical criticism of R&D based growth models generating scale effects in the steady state per-capita growth rate, and it is standard to assign it two alternative laws of motion. According to Segerstrom's (1998) interpretation of Jones' (1995) solution to the "strong scale effect" problem (Jones 2003), it is increasing in the accumulated stock of effective R&D, as:

$$\frac{\dot{X}(\omega, s)}{X(\omega, s)} = \mu I(\omega, s), \tag{TEG}$$

with positive μ, thus formalizing the idea that early discoveries fish out the easier inventions first, leaving the most difficult ones for the future.

Alternatively, Dinopoulos and Thompson (1998) suggest that

$$X(\omega, s) = kN(t), \tag{PEG}$$

with positive k, thereby formalizing the idea that it is more difficult to introduce a new product in a more crowded market.

Both formulations, as well as similar others rule out implausible "scale effects", but they have different long run implications: the first one - TEG[10] - implies that increasing difficulty of innovation causes per-capita GDP growth vanish over time unless an ever-increasing share of resources are invested in R&D, thereby requiring a growing educated population; by contrast PEG[11] formulation allows for sustained per-capita growth without population growth. In the present framework with quality improving consumer goods "growth" is interpreted as the increase over time of the representative consumer utility level.

Dinopoulos and Segerstrom (1999) carry out their analysis for both specifications of the difficulty index, and so will this paper do.

For industries targeted by positive R&D the constant returns to R&D and free entry and exit imply the no arbitrage condition

$$v(\omega, s) \equiv \frac{q_\omega \left(\lambda_\omega - 1\right) a}{\rho + I(\omega, s) - n} = b w_H X(\omega, s). \tag{11}$$

[10] Acronym "TEG" refers to the "temporary effects on growth" of policy measures such as R&D subsidies and tariffs: they cannot alter the steady state percapita growth rate, which is instead pinned down by the population growth rate, the negative dynamic externality parameter μ.

[11] Acronym "PEG" refers to the "permanent effects on growth" of policy measures such as R&D subsidies and tariffs: they can alter the steady state percapita growth rate.

The usual Arrow or replacement effect (Aghion and Howitt 1992) implies that the monopolist does not find it profitable to undertake any R&D at the equilibrium wages.

4 Balanced Growth Paths

We are now in a position to analyze the general equilibrium implications of the previous setting. As Dinopoulos and Segerstrom (1999) we will focus on the steady state properties of the model.

Since each final good monopolist employs unskilled labor worldwide to manufacture each commodity, the unskilled labor market equilibrium is

$$N(t)\theta_0 = a\int_0^1 q_\omega d\omega = a\int_0^1 \frac{N(t)}{a}\left(\frac{c}{\lambda_\omega}+\frac{G_\omega}{\lambda_\omega}\right)d\omega = N(t)\left[\Gamma c+\Omega\right] \tag{12}$$

Therefore:

$$c = \frac{\theta_0-\Omega}{\Gamma} \tag{13}$$

where $\Gamma = \int_0^1 \frac{1}{\lambda_\omega}d\omega$ and $\Omega = \int_0^1 \frac{G_\omega}{\lambda_\omega}d\omega$.

Eq.s (8), (10), and (11) imply that

$$\frac{N(t)}{\lambda_\omega a}\left(c+G_\omega\right) = bw_H X_\omega \frac{\rho+I_\omega-n}{a\left(\lambda_\omega-1\right)}, \tag{14}$$

which - since $w_H = \frac{\sigma}{\theta_0-\gamma}$ and (13) holds - can be rewritten as:

$$\frac{1}{\lambda_\omega}\left(\frac{\theta_0-\Omega}{\Gamma}+G_\omega\right) = \frac{b\sigma}{\theta_0-\gamma}x_\omega\frac{\rho+I_\omega-n}{\lambda_\omega-1}, \text{ for all } \omega\in[0,1], \tag{15}$$

where $x_\omega \equiv \frac{X_\omega}{N}$ denotes the population-adjusted degrees of complexity of product ω.

Similarly, skilled labor market equilibrium implies:

$$\left(\theta_0+1-2\gamma\right)\left(1-\theta_0\right)\phi/2 = b\int_0^1 I_\omega x_\omega d\omega. \tag{16}$$

4.1 Steady State Properties of the TEG Specification

In this section we will adopt the TEG specification of technological evolution and leave the analysis of the PEG specification to the next section.

In a steady state all per-capita variables are constant and therefore $\frac{\dot{X}(\omega,s)}{X(\omega,s)} = n$. Hence (TEG) implies: $I = n/\mu$. As usual in growth models with increasing complexity the steady state arrival rate of innovation in every industry is a linear increasing function of the population growth rate. Hence we can rewrite (15) and (16) as follows:

$$\frac{1}{\lambda_\omega}\left(\frac{\theta_0-\Omega}{\Gamma}+G_\omega\right)=\frac{b\sigma}{\theta_0-\gamma}x_\omega\frac{\rho+n/\mu-n}{\lambda_\omega-1}, \text{ for all } \omega\in[0,1], \tag{17}$$

$$(\theta_0+1-2\gamma)(1-\theta_0)\phi/2=b\frac{n}{\mu}\int_0^1 x_\omega d\omega\equiv b\frac{n}{\mu}\overline{x}. \tag{18}$$

Proposition 1 *Under the TEG specification if* $\frac{\Omega-\Gamma\overline{G}}{\Gamma}<\frac{n(1-2\gamma)\phi/2}{\mu\sigma(\rho+n/\mu-n)}$ *a steady state always exists for every distribution of* $\lambda_\omega>1$ *and* $G_\omega>0$, $\omega\in[0,1]$ *(where* $\overline{G}=\int_0^1 G_\omega d\omega$*). At each steady state the following properties hold:*

a.$G_\omega>G_{\omega'}$ *implies* $x_\omega>x_{\omega'}$ *and* $\partial x_\omega/\partial G_\omega>\partial x_{\omega'}/\partial G_{\omega'}$ *iff* $\lambda_\omega>\lambda_{\omega'}$

b. θ_0 *is an increasing function of* Ω

Proof of Proposition 1.a. Solving (17) for x_ω we get:

$$\left(\frac{\lambda_\omega-1}{\lambda_\omega}\right)\left(\frac{\theta_0-\Omega}{\Gamma}+G_\omega\right)\frac{\theta_0-\gamma}{b\sigma(\rho+n/\mu-n)}=x_\omega$$

deriving this w.r.t $G_\omega$we get

$$\frac{\partial x_\omega}{\partial G_\omega}=\left(\frac{\lambda_\omega-1}{\lambda_\omega}\right)\frac{\theta_0-\gamma}{b\sigma(\rho+n/\mu-n)}>0$$

since $\lambda_\omega>1$, $\theta_0>\gamma$ and $\rho>n$. From this derivative we can also see that $\partial x_\omega/\partial G_\omega>\partial x_{\omega'}/\partial G_{\omega'}$ when $\frac{\lambda_\omega-1}{\lambda_\omega}>\frac{\lambda_{\omega'}-1}{\lambda_{\omega'}}$ which is always true if $\lambda_\omega>\lambda_{\omega'}$.

Proof of proposition 1.b See the Appendix.

Remark

4.2 Steady State Properties of the PEG Specification

We now turn our attention to the analysis of the consequences of the PEG specification of technology. From eq. (PEG) it obviously follows that for all industries the population-adjusted difficulty index is always equal to a constant k. Therefore we can rewrite eq.s (15) and (16) as:

$$\frac{1}{\lambda_\omega}\left(\frac{\theta_0-\Omega}{\Gamma}+G_\omega\right)=\frac{b\sigma k}{\theta_0-\gamma}\frac{\rho+I_\omega-n}{\lambda_\omega-1}, \text{ for all } \omega\in[0,1], \tag{19}$$

$$(\theta_0 + 1 - 2\gamma)(1 - \theta_0)\frac{\phi}{2} = bk \int_0^1 I_\omega d\omega \equiv bk\overline{I}. \tag{20}$$

Then we derive:

Proposition 2 *Under the PEG specification, if* $\frac{\Omega - \Gamma \overline{G}}{\Gamma} < \frac{(1-2\gamma)\phi + 2bk(\rho - n)}{2\gamma}$*, a steady state exists for every distribution of* $\lambda_\omega > 1$ *and* $G_\omega > 0$ $\omega \in [0,1]$ *. At each steady state the following properties hold:*

a. $G_\omega > G_{\omega'}$ *implies* $I_\omega > I_{\omega'}$ *and* $\partial I_\omega / \partial G_\omega > \partial I_{\omega'} / \partial G_{\omega'}$ *iff* $\lambda_\omega > \lambda_{\omega'}$

b. θ_0 *is an increasing function of* Ω*.*

Proof of Proposition 2.a. Solving (19) for I_ω we get

$$I_\omega = \frac{\lambda_\omega - 1}{\lambda_\omega}\left(\frac{\theta_0 - \Omega}{\Gamma} + G_\omega\right)\frac{\theta_0 - \gamma}{b\sigma k} + (n - \rho)$$

$$\frac{\partial I_\omega}{\partial G_\omega} = \frac{\lambda_\omega - 1}{\lambda_\omega}\left(\frac{\theta_0 - \gamma}{b\sigma k}\right) > 0$$

since $\lambda_\omega > 1$ and $\theta_0 > \gamma$. Symmetrically to proposition 1.a from this derivative we can see that the effect of G_ω on R&D investment is greater the greater is the sector's quality jump λ_ω.

Proof of Proposition 2.b. See the Appendix.

5 Fiscal Policy Rules

Here we introduce different specifications of public expenditure and derive the two basic results of the paper.

The first fiscal policy we will study is a lump-sum rule, in the sense that it implies a perfectly symmetric expenditure in every sector.

- **Rule I (Perfect Symmetry)**: $G_\omega = \overline{G}$, which implies that $\Omega_I = \overline{G} \int_0^1 \frac{1}{\lambda_\omega} d\omega$.

The second rule is the one that allocate public spending more to the sectors with a bigger quality jump in innovation.

- **Rule II (Extreme Asymmetry):** $G_\omega = \overline{G}\frac{\lambda_\omega}{\overline{\lambda}}$ which implies that $\Omega_{II} = \frac{\overline{G}}{\overline{\lambda}}$.

Since $\frac{1}{\lambda_\omega}$ is a strictly convex function, Jensen's inequality implies that $\Omega_I > \Omega_{II}$.

The third rule that we take into account is a linear combination of the two extreme rules.

- **Rule III (Convex Combination):** $G_\omega = (1-\alpha)\overline{G} + \alpha\overline{G}\frac{\lambda_\omega}{\overline{\lambda}}$, with $0 \leq \alpha \leq 1$, which implies $\Omega_{III} = \overline{G}\left[\int_0^1 \frac{1-\alpha}{\lambda_\omega} d\omega + \frac{\alpha}{\overline{\lambda}}\right]$ and $\partial\Omega_{III}/\partial\alpha = \overline{G}\left[-\int_0^1 \frac{1}{\lambda_\omega} d\omega + \frac{1}{\overline{\lambda}}\right]$.

Jensen's inequality implies that $\partial\Omega_{III}/\partial\alpha < 0$, thus when we move from a symmetric rule to a rule that promote more public spending in sectors with quality jumps above the average we have a decrease in Ω which, according to propositions 1.b and 2.b, implies a decrease in the share of the population which decide to acquire skills θ_0.

Proposition 3 *Every move from a symmetric rule to a rule that promotes more the sectors with quality jumps above the average produces a decrease in Ω, which implies a decrease in the share of the population which decide not to acquire skills, θ_0 (thus, $\partial\theta_0/\partial\alpha < 0$). As a consequence of the decline in θ_0 this policy change will also increase the skill premium w_H (thus, $\frac{\partial(w_H/w_L)}{\partial\alpha} > 0$).*

Proof. Deriving Ω_{III} with respect to α we get $\partial\Omega_{III}/\partial\alpha = \overline{G}\left[-\int_0^1 \frac{1}{\lambda_\omega} d\omega + \frac{1}{\overline{\lambda}}\right]$ and Jensen's inequality implies that $\partial\Omega_{III}/\partial\alpha < 0$. Thus, a shift to a more asymmetric spending (an increase in α) decreases Ω that, according to propositions 1.b and 2.b, implies a decrease in the share of the population that decide not to acquire skills, θ_0. Since $w_H = \frac{\sigma}{\theta_0 - \gamma}$, we can conclude that an increase in α increases wage inequality.

Proposition 3 contains the first result of the model: when government switches to a policy that promotes more high-tech sectors, as it has been the case in the US during the 1980's and 1990's, there is a decrease of the relative supply of unskilled workers and an increase of the skill premium. This theoretical result matches two fundamental stylized facts of the US labor market: the increase in the skill premium and the increase in the relative supply of skilled workers (see Acemoglu 2002 figure 1).

Proposition 4 *An increase in per-capita government investment $\overline{G}$ does not have any effect on the skill premium under perfectly symmetric spending (rule 1), but it increases the skill premium under asymmetric spending (rules 2 and 3).*

Proof. See the Appendix.

This is the second basic result of the paper and the economic intuition for it goes as follows. In this stylized economy there is no way public expenditure can increase equilibrium revenues for manufacturing firms in the aggregate. In fact, by taxing consumers it induces private expenditure to drop by the same aggregate amount as G, because government budget is always balanced. In case public expenditure is evenly distributed across sectors (policy I), an increase in $\overline{G}$ generates an equiproportional decrease in private expenditure (due to the symmetric Cobb-Douglas preference structure), that exactly matches the increase in government expenditure: as a consequence there will be no effect on the skill premium. If instead the increase in $\overline{G}$ is allocated more than proportionally in the sectors that are innovating more strongly than average (policies II and III) the private equiproportional negative income effect would be more than compensated in the sectors with above average quality jumps. This implies an increase in the revenue of those sectors matched by a decrease in the revenue in the sectors with below average quality jumps. Since one dollar more of revenue in the high tech sectors yields more additional profits than those lost with one dollar less in the low tech sectors - because high tech means higher mark-ups - the net result would be an increase in aggregate profits. Since skilled wage incomes basically consists of expected profits, policies II and III de facto redistribute income from the low skilled to the high skilled. Therefore higher $\overline{G}$ implies higher skill premium and more incentive to educate.

6 Calibration

In this section we calibrate a two-sector version of the model. All the results we obtained for the model with a continuum of sectors hold for this shortcut version. The calibration affords an estimate of the quantitative effects of government policy change on the skill premium, which we compare with the actual time path of the premium so as to assess the model's empirical relevance.

The exercise consists of calibrating the 8 parameters of the model $\{D, Tr, \rho, \gamma, n, \mu, \lambda_1, \lambda_2\}$ to match some key aggregate features of the data. For the calibration we choose a period of 21 years, from 1978 to 1998, and we first observe the increase in the skill premium over this period generated by our key policy variable α (which is an index of the composition of public spending)[12], and then compare it with the real increase in the skill premium observed in the data. Secondly, we simulate the model for the entire period to obtain an image of the relation between the model prediction and the observed premium through time.

The calibration of some parameters is standard. For example, we choose $\rho = 0.03$ to match an annual interest rate of 3 percent, and we choose the total life time $D = 40$ as in Dinopoulos and Segerstrom (1999), and the total training time $Tr = 4$, to match the average years of college in the USA. We choose the growth rate of population n as 1 percent and the threshold γ to bound the relative supply of unskilled workers above 75 percent of the workforce as in Dinopoulos and Segerstrom (1999). We use BEA data for the model's two policy variables, the total government per-capita spending $\overline{G}$ and the share of government spending going to the high-tech sectors α. More precisely, we consider equipment and software as the high-tech sector and structures as the low-tech and use BEA data where total government investment is broken down in investment in structures and investment in equipment and software.

The crucial parameters of the calibration are the R&D difficulty index μ, and the quality jumps of the low and high-tech sectors, λ_1 and λ_2 respectively. We jointly estimate these parameters using the data on the USA GDP growth rate and the estimates of the yearly average technical change in equipment and in structures obtained in Gort, Greenwood and Rupert (1997) and Cummings and Violante (2002). Gort, Greenwood and Rupert find that the rate of structure-specific technological progress is about 1% a year

[12] See proposition 3.

and Cummings and Violante (2002) find that the average rate of technological progress in equipment and software is 4% in the post WWII period, 5% after 1975 and 6% in the 1990's. We thus set the quality jump in the first sector to 1% a year ($\lambda_1 = 1.01$), and the quality jump in the sector two to 5% a year ($\lambda_2 = 1.05$)[13]. Using the TEG version of the model we obtain the following growth rate:

$$g = \frac{\dot{u}}{u} = I \int_0^1 \log \lambda_\omega d\omega = \frac{n}{\mu}\frac{1}{2}(\ln \lambda_1 + \ln \lambda_2) \quad (21)$$

From Penn World tables we get an average GDP growth rate for the period 1978-1999 in the US of 3.2% and using the quality jumps calibrated as explained above we obtain a value for the R&D difficulty index μ of 1.6. Equation (A.1.1) expresses the equilibrium share of unskilled workers as function of Ω (the variable directly influenced by the policy measure). Substituting the $w_H = \frac{\sigma}{\theta_0 - \gamma}$ into (A.1.1) we obtain a relation between the skill premium and Ω [14]. Table 2 below summarizes our calibration.

TABLE II

SUMMARY OF CALIBRATION

paremeter	value	moment to match	source
D	40	life time after college	Dinopoulos-Segerstrom 1999
T	4	years of college	Dinopoulos-Segerstrom 1999
ρ	$0,03$	interest rate	Dinopoulos-Segerstrom 1999
n	0.01	population growth rate	Dinopoulos-Segerstrom 1999
γ	0.75	low-bound for the share of unskilled workers	Dinopoulos-Segerstrom 1999
$\boldsymbol{\mu}$	0.14	GDP growth rate of 3.2%	Penn World Tables
λ_1	1.01	structures-specific technical change	Gort, Greenwood, Rupert (1999)
$\boldsymbol{\lambda}_2$	1.05	technical change in equipment & software	Cummins and Violante (2002)

Using these parameters, BEA data on total government spending G on the share of public spending that goes to high-tech sectors α and Penn World Tables data on the US population, we obtain the following predictions: when we consider the mere effect of a the increase in the share of public spending in equipment

[13] We choose 5% because we calibrate the model for the period 1978-99.

[14] Notice that w_H is the skill premium in our model because we normalized the wage of unskilled workers w_L to 1. It is easy to show that using spending rule III we get the follwing expression for Ω.

$$\Omega = \frac{\overline{G}}{2}\left[(1-\alpha)\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right) + \frac{2\alpha}{\overline{\lambda}}\right]$$

Thus, after substituting the calibrated λ's we get Ω as a function of the level $\overline{G}$ and the composition α of public spending.

and software the model explains 43 percent of the observed increase in the skill premium from 1978 to 1998. We then consider the joint effect of the increase in the level and the share of government investment in equipment and software and this time the share of the observed increase in the wage premium explained by the model rises to 63 percent.

Figure 5 shows the predicted skill premium when we simulate the sequence of steady states generated respectively by the observed changes in the composition of government spending (α in the model), keeping the level constant, and by the joint observed changes in the composition and in the level of per-capita government investment. We can see that the findings of proposition 3 and 4 are supported by the simulation's results; that is, when we perturb the model's steady state with the real changes in the composition of public spending we replicate an important part of the dynamics of the skill premium. When we add the observed shock in the level of spending the model's fit improves substantially.

In Table III below we study the sensitivity of the model to changes in the difference in quality jumps between the two sectors. Keeping λ_1 constant, we vary λ_2 according to the estimations of the average technical change in equipment and software obtained by Cummins and Violante (2002) for the post-WWII period (4 percent), the period after 1975 (5 percent) - used in the calibration above- and the 1990's (6 percent).

TABLE III

Sensitivity analysis

Policy shock	$\lambda_2 = 1.04$	$\lambda_2 = 1.05$	$\lambda_2 = 1.06$
α	0.21	0.43	0.64
$\overline{G}$	0.06	0.08	0.09
α and $\overline{G}$	0.39	0.63	0.98
Percentage of the observed change in the skill premium explained by each policy shock: 1978-1998			

We do the experiment for each policy shock (composition and level of spending) and we find that the percentage of the observed skill premium explained by the model improve substantially with the increase in the quality jump difference in the two sectors. Notice that, intuitively enough, the effect of the increase in the level of per-capita public spending is small when the composition is kept constant at its 1978 level ($\alpha = 0.2$). But when we allow for the joint change in the composition and the level of public spending we have an overall effect which is bigger than the sum of the two separate effects. This is due to the fact that when the degree of spending asymmetry is low (low α) each increase in $\overline{G}$ will have a small market size effect, the increase in total profits will thus be low and, consequently, the increase in the wage of skilled workers will be small. On the other hand, when the spending rule is more asymmetric a bigger share of each dollar of additional public spending will go to the high-tech sectors, thus resulting in a bigger demand for innovation and skilled workers. Finally, it is worth noting that when we consider a difference in the quality jumps of 5 percentage points the joint effect of the two policy shocks reproduces almost all the observed 28 percent increase in the skill premium between 1978 and 1998.

7 Final Remarks

This paper has shown that US technology policy has an important role in explaining the wave of innovation that hit the US economy in the recent decades, its bias towards skilled labor and its effects on the wage structure. Moreover, the model provides an endogenous mechanism to link technical change to wage inequality -endogenous in the sense that innovation activity comes from profit-maximizing behavior of firms. It represents the first attempt to evaluate the effects of government policy on wage inequality and it is amenable to many extensions. In the first place, further research is needed to fill the data gap that prevents a more rigorous evaluation of the magnitude of the policy effects on wages. Once in possession of a more complete data set on government spending in high-tech sectors, an interesting extension could be to open up our economy and analyze the joint effects of trade liberalization and technology policy on the skill premium. Another immediate extension consists of modeling in addition the role policies aimed at reducing the cost of innovation. In this case the policy mechanisms contained in Howitt (1999) and Segerstrom (1998) suggest easy ways to introduce in our model the effects of R&D subsidies (i.e. R&D tax credit) on innovation activity and on the wage premium. The other policy measures aimed at reducing the cost of innovation can also be introduced in the model but unfortunately they are not easily quantifiable[15]. Further research could be targeted to quantify the magnitude of these public incentives to innovation in order to asses the overall effect of the post Cold War technology policy on the wage structure.

8 Appendix

Proof of the existence of the steady state with TEG. Solving (17) for x_ω and integrating it w.r.t. ω we get:

[15] For instance, the FTC provides data on the percentage of mergers subjects to second requests, which is the second round of information on a transactoin requested by the FTC after the ordinary first request (it can be interpreted as a sign of FTC's serious intentions to challenge the merger). Unfortunately it is not easy to include similar variables in macro models in order to asses their effects on the wage structure. Similar consideration holds for NSF data on the number of domestic research joint ventures and on public-private research collaboration (like the number of patent applications and the number of CRADA).

$$\overline{x} = \frac{\theta_0 - \gamma}{b\sigma(\rho + n/\mu - n)} \left[(\theta_0 - \Omega)\left(\Gamma^{-1} - 1\right) + \left(\overline{G} - \Omega\right)\right] \tag{A1}$$

and substituting this into (18) we get:

$$(\theta_0 + 1 - 2\gamma)(1 - \theta_0)\phi/2 = \frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)} \left[(\theta_0 - \Omega)\left(\Gamma^{-1} - 1\right) + \left(\overline{G} - \Omega\right)\right] \tag{A.1.1}$$

The LHS of this eq. (A11) is a strictly concave quadratic polynomial with roots on $2\gamma - 1$ and 1, and the RHS of eq. (A11) is a strictly convex quadratic polynomial with roots γ and $\frac{\Omega - \Gamma\overline{G}}{1-\Gamma}$. It follows that, if the stated parameter restrictions are satisfied, there exists one and only one real and positive solution $\theta_0 \in (\gamma, 1)$[16].

Proof of Proposition 1.b Rearranging (A11) we get the single polynomial in θ_0 and Ω.

$$F(\theta_0; \Omega) = \frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)} \left[(\theta_0 - \Omega)\left(\Gamma^{-1} - 1\right) + \left(\overline{G} - \Omega\right)\right] - (\theta_0 + 1 - 2\gamma)(1 - \theta_0)\phi/2 \tag{A.1.2}$$

Using the Implicit Function Theorem we get:

$$\frac{d\theta_0}{d\Omega} = \frac{-\partial F/\partial\Omega}{\partial F/\partial\theta_0} =$$

$$= \frac{\frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)\Gamma}}{\frac{n}{\mu\sigma(\rho + n/\mu - n)}\left[(\theta_0 - \Omega)\left(\Gamma^{-1} - 1\right) + \left(\overline{G} - \Omega\right)\right] + \frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)}\left(\Gamma^{-1} - 1\right) + \phi(\theta_0 - \gamma)} > 0$$

This results follows from the fact that $\theta_0 > \gamma$, $\rho > n$, $\Gamma^{-1} > 1$ and finally, from (A1) we know that the expression inside the square brackets is greater than zero. Q.E.D

Proof of the existence of a steady state with PEG: Solving (19) for I_ω we get

[16] The proof follows from the fact that the specified parameter restriction allows the intercept (the value of the polynomial at $\theta_0 = 0$) of the LHS polynomial to be bigger than in intecept of the RHS polynomial.

$$I_\omega = \frac{\lambda_\omega - 1}{\lambda_\omega}\left(\frac{\theta_0 - \Omega}{\Gamma} + G_\omega\right)\frac{\theta_0 - \gamma}{b\sigma k} + (n - \rho)$$

integrating this w.r.t. ω yields

$$\overline{I} = \frac{\theta_0 - \gamma}{b\sigma k}\left[(\theta_0 - \Omega)\left(\Gamma^{-1} - 1\right) + \left(\overline{G} - \Omega\right)\right] + (n - \rho) \qquad \text{(A2)}$$

and substituting in (20) we obtain

$$(\theta_0 + 1 - 2\gamma)(1 - \theta_0)\,\phi/2 = \frac{(\theta_0 - \gamma)}{\sigma}\left[(\theta_0 - \Omega)\left(\Gamma^{-1} - 1\right) + \left(\overline{G} - \Omega\right)\right] + bk(n - \rho) \qquad \text{(A.2.2)}$$

The LHS of this eq. (A11) is a strictly concave quadratic polynomial with roots on $2\gamma - 1$ and 1, and the right hand side of eq. (A11) is a strictly convex quadratic polynomial with two positive roots $\gamma - bk(n-\rho)\sigma$ and $\frac{bk(\rho-n)\sigma + (\Omega - \Gamma\overline{G})\Gamma^{-1}}{\Gamma^{-1}-1}$ it follows that, if the specified parameters restrictions are satisfied, there exists one and only one real and positive solution $\theta_0 \in \left(\max\left\{\gamma - bk(n-\rho)\sigma, \frac{bk(\rho-n)\sigma + (\Omega - \Gamma\overline{G})\Gamma^{-1}}{\Gamma^{-1}-1}\right\}, 1\right)$.[17]

Proof of proposition 2.b. From (A22), proceeding similarly to what we did for the TEG case above, we get:

$$\frac{d\theta_0}{d\Omega} = -\frac{\partial F/\partial\Omega}{\partial F/\partial\theta_0} = \frac{\frac{(\theta_0 - \gamma)}{\Gamma}}{\left[(\theta_0 - \Omega)\left(\Gamma^{-1} - 1\right) + \left(\overline{G} - \Omega\right)\right] + (\theta_0 - \gamma)\left(\Gamma^{-1} - 1\right) + \Gamma\sigma\phi\,(\theta_0 - \gamma)} > 0$$

since, as we saw above, $\theta_0 > \gamma$, $\rho > n$, $\Gamma^{-1} > 1$ and for (A2) the term under the square brackets is positive. Q.E.D.

Proof of proposition 4. Here we prove the proposition only for the TEG specification. Following the same steps it is easy to obtain a proof for the PEG case. From (A.1.2) and using the implicit function theorem we get:

Using the Implicit Function Theorem we get:

$$\frac{d\theta_0}{d\overline{G}} = \frac{-\partial F/\partial\overline{G}}{\partial F/\partial\theta_0} =$$

$$= \frac{-\frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)\Gamma}\left[1 - \frac{1}{\Gamma}\left(\frac{\partial\Omega}{\partial\overline{G}}\right)\right]}{\frac{n}{\mu\sigma(\rho + n/\mu - n)}\left[(\theta_0 - \Omega)\left(\Gamma^{-1} - 1\right) + \left(\overline{G} - \Omega\right)\right] + \frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)}\left(\Gamma^{-1} - 1\right) + \phi\,(\theta_0 - \gamma)}$$

[17] It follows from the same reasoning we did for the TEG case's proof of the existence of the steady state.

- Rule I (Perfect Symmetry):

$$-\partial F/\partial \overline{G} = -\frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)\Gamma}\left[1 - \frac{1}{\Gamma}(\Gamma)\right] = 0$$

Hence per-capita government investment does not have any affect on the skill premium.

- Rule II (Extreme Asymmetry):

$$-\partial F/\partial \overline{G} = -\frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)\Gamma}\left[1 - \frac{1}{\Gamma}\left(\frac{1}{\overline{\overline{\lambda}}}\right)\right] = -\frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)\Gamma}\left[\Gamma - \left(\frac{1}{\overline{\overline{\lambda}}}\right)\right]\frac{1}{\Gamma} < 0$$

since, by Jensen's inequality, $\Gamma > \frac{1}{\overline{\overline{\lambda}}}$. Thus, an increase in $\overline{G}$ decreases the share of unskilled θ_0 and increases the skill premium ($w_H = \frac{\sigma}{\theta_0 - \gamma}$).

- Rule III (convex combination):

$$-\partial F/\partial \overline{G} = -\frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)\Gamma}\left\{1 - \frac{1}{\Gamma}\left[(1-\alpha)\Gamma + \frac{\alpha}{\overline{\overline{\lambda}}}\right]\right\} = -\frac{n(\theta_0 - \gamma)}{\mu\sigma(\rho + n/\mu - n)\Gamma}\left[\Gamma - \frac{1}{\overline{\overline{\lambda}}}\right]\frac{\alpha}{\Gamma} < 0$$

As in the extreme asymmetry also in this intermediate level of asymmetry in public spending the increase in the per-capita spending as a positive effect on the skill premium.

9 Data Appendix

Data for Figure 5: The data on the share of government investment in equipment and software (α in the model) and on the total level of government investment is taken from BEA Nipa tables section 5 and 7. The population levels used to obtain the per-capita total government investment (G in the model) is taken from Penn World tables 1999. The observed skill premium is taken from Krusell, Ohanian, Rios-Rull and Violante (2000) from 1978 to 1992 and from BLS Current Population Survey from 1993 to 1999.

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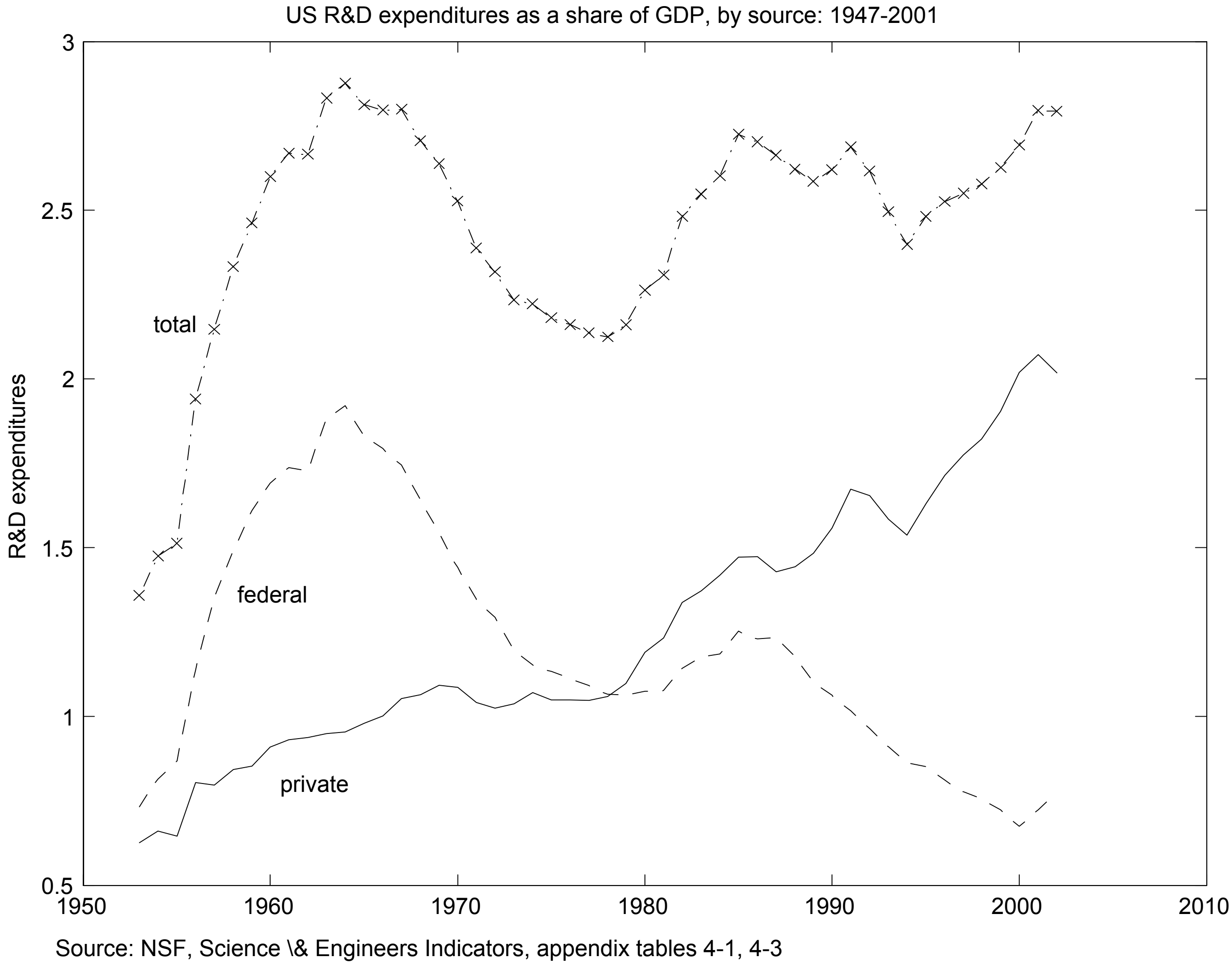
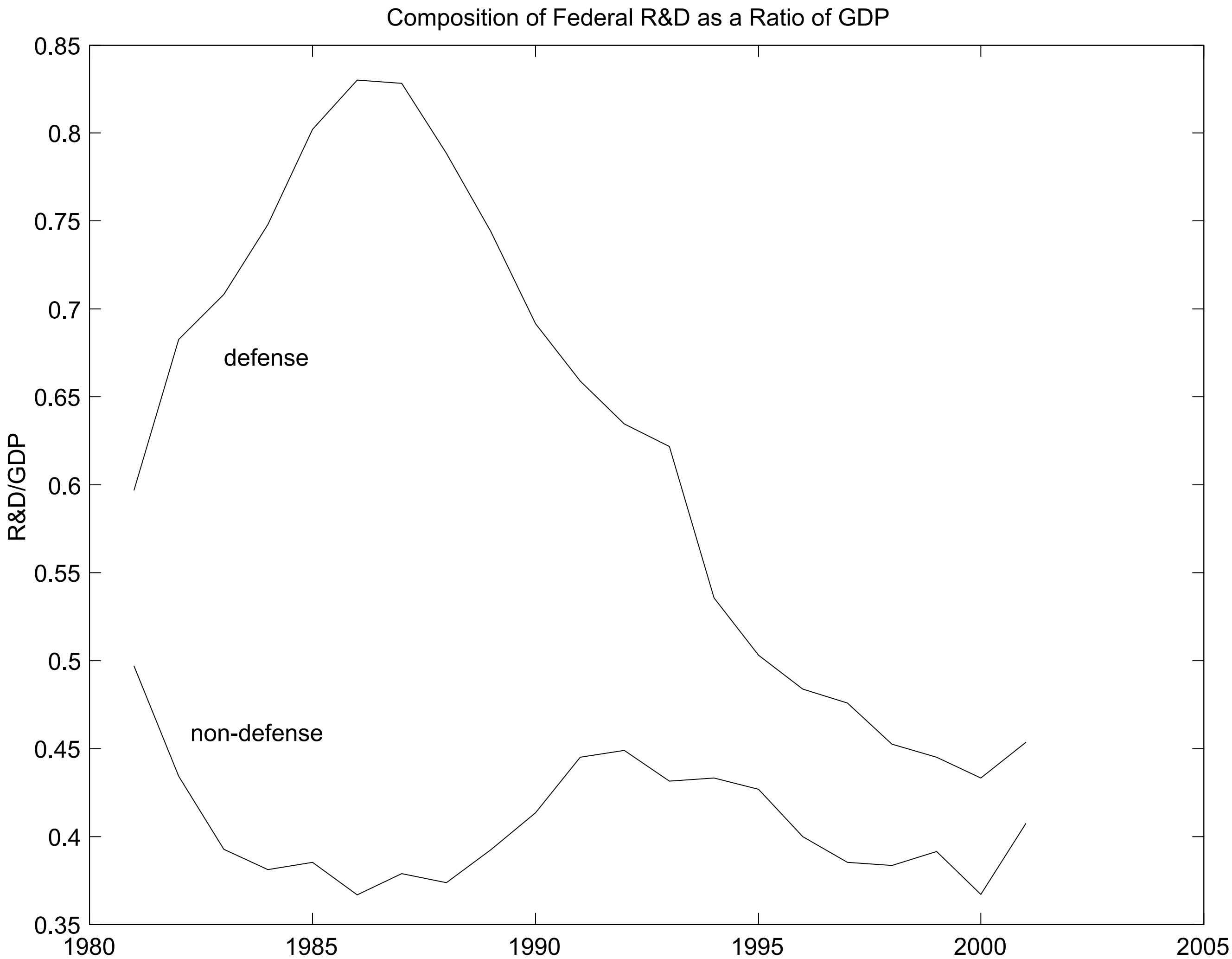

US R&D expenditures as a share of GDP, by source: 1947-2001
R&D expenditures
total
federal
private
3
2.5
2
1.5
1
0.5
1950
1960
1970
1980
1990
2000
2010
Source: NSF, Science \& Engineers Indicators, appendix tables 4-1, 4-3

Figure 1:



Source: NSF, Federal R&D funding by Budget Function (Special Report), Historical tables

Figure 2:

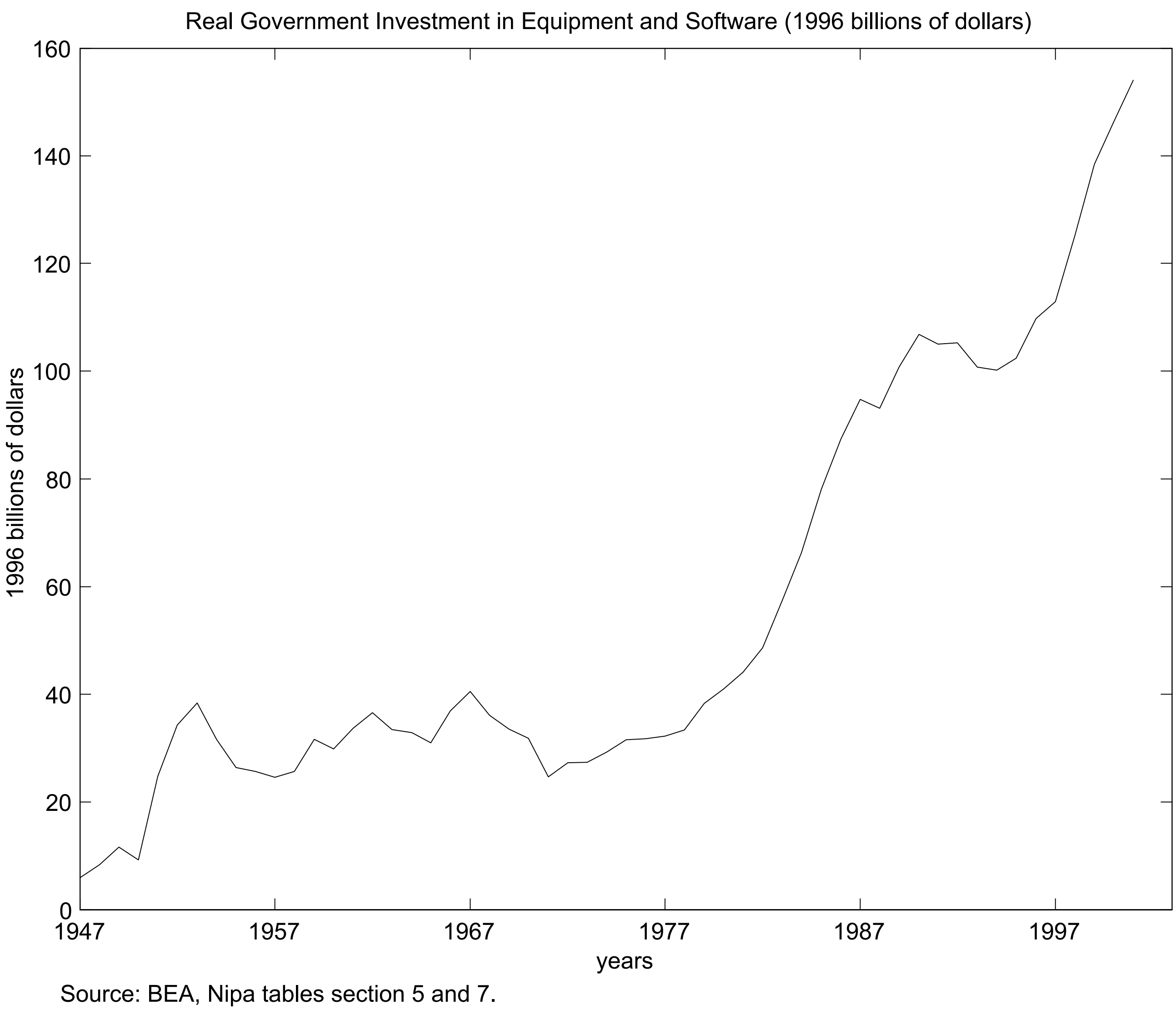

Real Government Investment in Equipment and Software (1996 billions of dollars)
1996 billions of dollars
0
20
40
60
80
100
120
140
160
1947
1957
1967
1977
1987
1997
years
Source: BEA, Nipa tables section 5 and 7.

Figure 3:

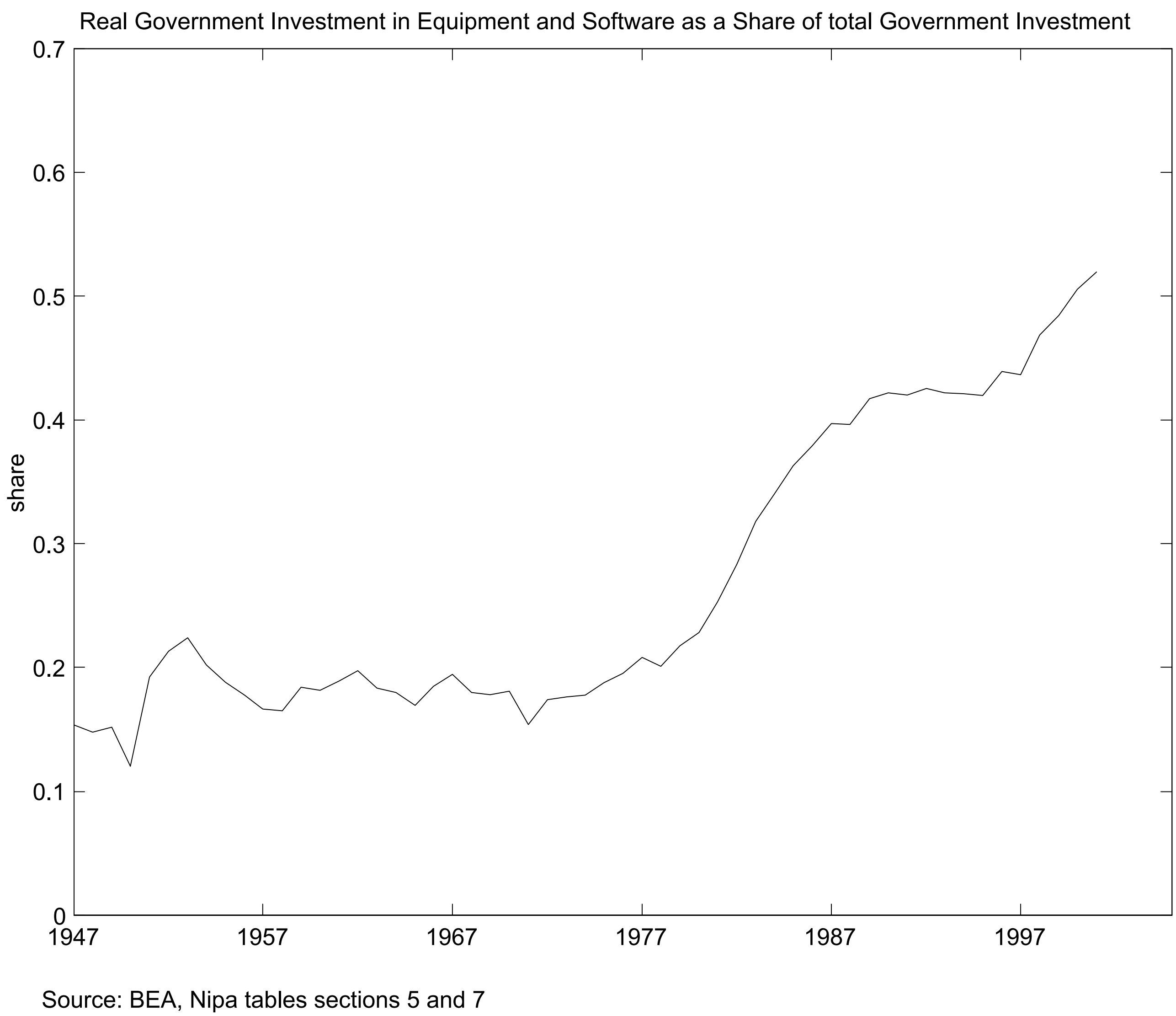

Real Government Investment in Equipment and Software as a Share of total Government Investment
share
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1947
1957
1967
1977
1987
1997
Source: BEA, Nipa tables sections 5 and 7

Figure 4:

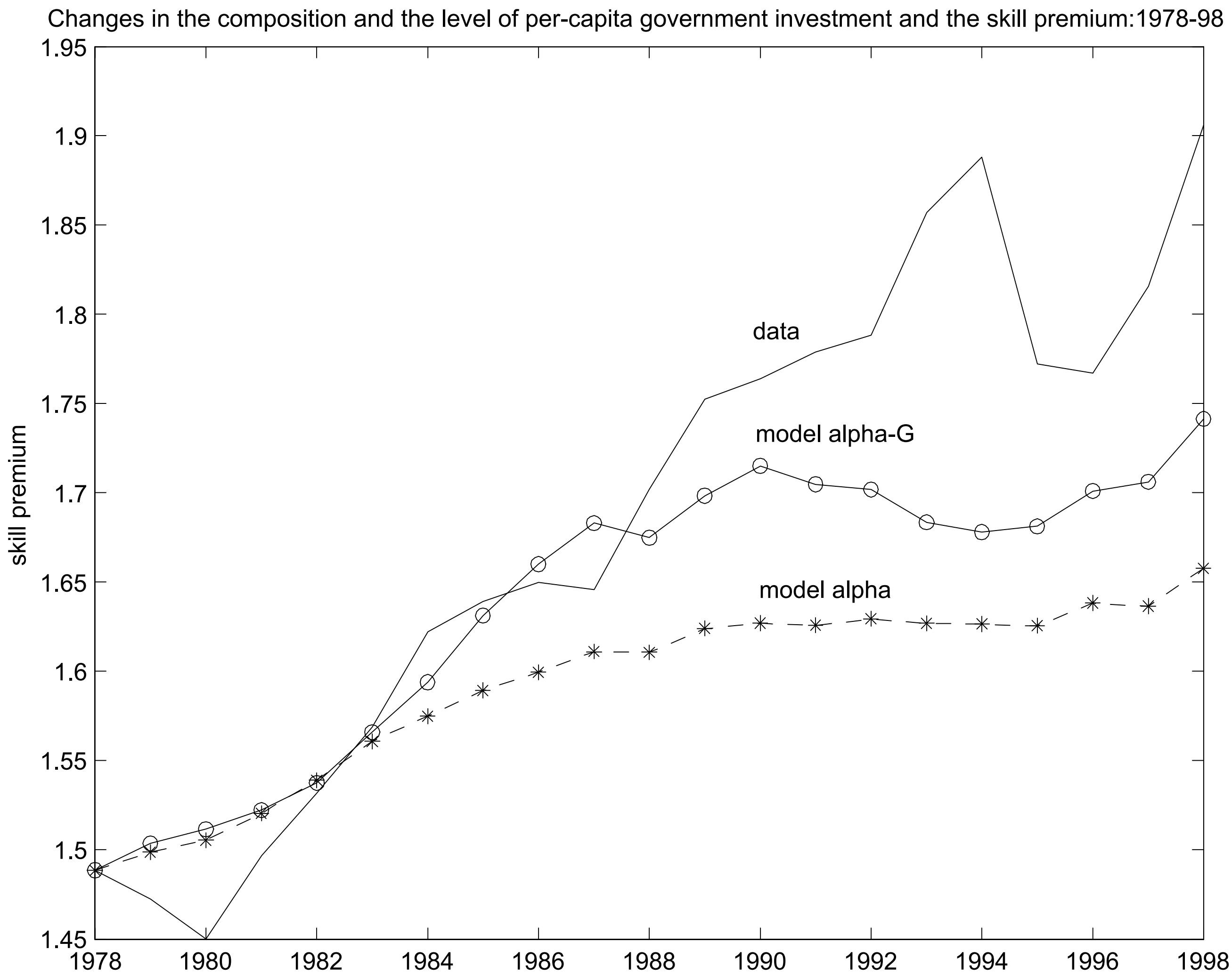

Changes in the composition and the level of per-capita government investment and the skill premium:1978-98
skill premium
1.95
1.9
1.85
1.8
1.75
1.7
1.65
1.6
1.55
1.5
1.45
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
data
model alpha-G
model alpha

Figure 5: