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The Role of Trade in Technology Diffusion

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ABSTRACT

This paper develops a two-country model in which trade is central to the process by which technology diffuses from the innovating country (North) to the backward country (South). Innovation in North leads to the introduction of higher-quality equipment goods that South can import only after some resources have been spent to adapt those equipment goods to the local conditions of South. Barriers to trade and policies that increase the cost of adapting equipment goods to the local environment decrease the rate of technology adoption, leading to a lower steady state relative income level in South. The model is calibrated to quantify this negative impact of barriers to trade and technology adoption on relative income levels and explore some additional implications of the model.

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1 Introduction

Most economists agree that technology diffusion is central to the process by which poor countries keep up with – or maybe even catch up to – the productivity of rich countries. There is disagreement about the way in which such diffusion takes place. Mankiw (1995), for instance, argues that technological change spreads through the world in a rapid and costless fashion, while Parente and Prescott (1994) believe that technology must be acquired in a slow and costly process of technology adoption. Still, even such radically different perspectives share the view that it is technology diffusion that allows all countries to grow at the world's rate of technological change in the long run.

This paper is concerned with the diffusion of technology when such technology is embodied in inputs.[1] It seems natural to think that trade is central to the process by which such embodied knowledge spreads across countries. According to this view, poor countries benefit from technological change in rich countries by importing inputs embodying more productive techniques. Importing new inputs is not easy, however, not only because people must learn about the new production process associated with them, but also because of the costs of adapting those production processes to the local environment and setting up the infrastructure needed for the actual importing, marketing, maintenance and support for the new equipment.[2] This explains why firms engaged in the production of advanced inputs often maintain local offices in many of the countries to which they export their products (see Ciccone (1995) for a more extensive discussion of this issue); it also explains why inputs are often imported by unique local distributors and why import barriers decrease the variety of goods imported (see Romer, 1994, and Klenow and Rodríguez-Clare, 1996). Klenow and Rodríguez-Clare (1996) also show that input variety (i.e., number of countries from which a particular input is imported) increases with a country's GDP, a

[1] Greenwood, Hercowitz and Krusell (1995) find that investment-specific or embodied technological change accounts for 60% of the total factor productivity growth in the U. S. in the last four decades. It thus appears natural to focus on the diffusion of embodied technology across countries.

[2] For examples of the difficulties involved in technology adoption see Teece (1977) and Grilliches (1957). The costs of technology adoption should also include the costs of determining whether a particular input is suitable for a country that has different soil conditions, environmental regulations, working traditions and labor skills than the countries where those inputs are introduced.

result that suggests the existence of fixed import costs.[3]

The previous observations suggest a characterization of technology diffusion in which advanced countries introduce new inputs embodying improved techniques, which are later used by developing countries after the necessary adaptation has taken place. In this paper I construct a model to capture this process of technology diffusion. The model is similar in spirit to the model of technology adoption developed by Parente and Prescott (1994) but with trade central to the process by which technology diffuses across countries. There are two countries, North and South. Innovation occurs only in North, where entrepreneurs spend resources to upgrade the quality of equipment goods as in the quality-ladder model of Grossman and Helpman (1991). South can potentially benefit from innovation in North by importing the higher quality equipment goods introduced in North, but this can only be done after some resources have been spent to adapt those equipment goods to the local conditions of South. I refer to this process of adaptation as technology adoption.

The equilibrium rate of technology adoption in South is determined by the equality between its cost and the profits made by importing improved equipment goods to South. In turn, the rate of technology adoption determines the steady-state gap between the average quality of equipment goods used in South and the average quality of equipment goods used in North. In steady state both regions grow at the same rate, which is determined by the rate of innovation in North; the rate of technology adoption in South only serves to determine the gap in income per capita levels between the two countries.

The model identifies three parameters that determine the rate of technology adoption in South: (1) the cost of technology adoption, (2) population size (a scale effect), and (3) trade barriers. High costs of technology adoption (which may be due to excessive regulation, corruption or high taxes), high barriers to trade, and low population size all lead to a low rate of technology adoption and thus a low relative income level in steady state.

An important question here is whether technology adoption might be too high in steady state, in which case barriers to trade or policies that increase the cost of technology adoption could actually improve welfare.

[3] Also suggestive of fixed costs of importing is the result that, in the context of Costa Rica, input variety increases with market size as measured by total expenditure on a particular input (see Klenow and Rodríguez-Clare, 1996).

This possibility arises from the fact that, just as in models of innovation, technology adoption generates a negative externality through the profit-stealing effect. In Section 3 I show that this does not arise in this model, since the positive externalities associated with technology adoption (a consumption externality and a price-distortion externality) always outweigh the negative externality associated with the profit-stealing effect. Thus, policies that reduce technology adoption will reduce welfare.

What is the quantitative significance of the impact of tariffs or barriers to technology adoption on income per capita suggested by the model? Section 4 calibrates the model to U. S. data to look into this matter. The results indicate that small barriers to technology adoption may have a large impact on income per capita levels. Starting with a relative income level of 0.55 (i.e., an income per capita in South that is fifty five percent of the level in North), a 10 percent rise in the cost of technology adoption leads to an 8 percent decline in relative income. The results also indicate that the presence of technology adoption costs makes trade barriers more costly than in traditional trade models. For instance, starting with a steady-state relative-income level of 0.55, a 10 percent tariff on equipment goods leads to a fall in steady-state relative income in South of 5.2 percent if the rate of technology adoption is held constant; once we take into account the impact of the tariff on technology adoption the fall in relative income in South becomes 8.5 percent. (The tariff has a strong impact on relative income even when holding technology adoption constant because of the effect on the use of equipment and other complementary kinds of capital.)

The result that trade barriers have a large negative impact on income levels is related to an argument recently made by Paul Romer (1994). Romer shows that the existence of fixed import costs implies that tariffs may generate significant welfare losses through the reduction of the variety of goods imported. More importantly, he shows that such welfare losses can be significantly higher than the production and consumption distortions (i.e., Harberger Triangles) emphasized by traditional trade theory (see Klenow and Rodríguez-Clare (1996) for an empirical implementation of this idea). I show here that tariffs have a similar effect in the presence of technology-adoption costs, since they make it less profitable to import the equipment goods just recently introduced in North, thus forcing producers in South to use older and less productive inputs.

This is particularly interesting in light of recent papers showing that trade may have a negative impact on development by reducing human capital accumulation or learning by doing (Stokey (1991) and Young (1991)). These results run counter to the common view that trade has a positive impact on the process of development, but they do suggest that the role of trade in development depends on whether development is driven by capital accumulation, learning by doing, technology adoption, or something else. This paper shows that as long as technology adoption plays an important role in economic development, then international trade becomes essential for developing countries. This result is consistent with recent papers by Coe, Helpman and Hoffmeister (1995) and Keller (1996), who show that more trade with high R&D countries is associated with higher total factor productivity levels.

In Section 4 I also consider the implications of the calibrated model for the international dispersion of income per capita levels. Since I do not have any data on the cost of technology adoption for different countries I rely on an indirect approach for this exercise. Given the tariff on equipment goods and the rate of technology adoption, the model generates a prediction for the relative price of equipment. Using data for tariff rates from Lee (1994) and for equipment prices from Jones (1994) I can then determine the model's implied rate of technology adoption. From this I obtain the model's implied relative income level for each country for which I have the relevant data. The results show that the model can account for differences in income per capita levels of up to a factor of 4. It does not seem posible to explain the extreme poverty observed in some countries as a result of the technological backwardness of the equipment goods they use.

The calibrated model may also serve to explain the fact that the relative price of producer durables is inversely related to income per capita, as described by De Long and Summers (1991) and Jones (1994). Using data provided by Charles Jones, I have plotted the 1980 price of equipment relative to consumption (with the U.S. price normalized to 1) against 1980 output per worker relative to the U.S. in Figure 1. There is a negative and significant correlation between these two variables: the regression of output per worker relative to the U.S. on the relative price of equipment (also relative to the U.S.) gives a negative and significant coefficient of -0.24 (t-statistic is -5.78, R^2 is 34). According to the model, this negative correlation arises because the high technology gap prevailing in poor countries allows successful technology adopters to charge high mark-ups, thus increasing the relative price of equipment there. For instance, the implied average mark-up charged by successful technology adopters in a country with a 30 percent tariff on equipment goods and a steady-state relative income level of 1/2 is 50 percent, which implies a measured relative price of equipment of almost twice the corresponding U.S. price.

1.1 Relation to the Recent Literature on Technology Adoption

There are several models of technology adoption that are related to the one I present here. Parente and Prescott (1994) model technology adoption as a process by which individual firms incorporate "world knowledge" into their production process. They assume that it is less costly to appropriate world knowledge for firms that are further behind technologically. Thus, barriers to technology adoption lead to lower steady-state relative income levels rather than lower growth rates. The model I develop here shares this basic result, but it does not rely on assuming that technology adoption is easier for technologically backward countries. Instead, the result arises from the assumption that technology adoption entails jumping to the "quality frontier" for a particular equipment good (this feature is also present in Eaton and Kortum, 1994). Thus, technology adoption has a stronger effect on the technology gap in backward countries.

Perhaps a more fundamental difference between Parente and Prescott and the model developed here has to do with the way technology is modeled. Whereas Parente and Prescott interpret technology as firm-specific disembodied knowledge that allow firms to produce more with given resources, I think of technology as embodied in higher-quality equipment goods. This interpretation of technology as embodied in equipment goods is what allows me to consider the role of trade in technology diffusion.

Grossman and Helpman (1992) have developed a series of North-South models in which the North introduces new goods which are then copied or imitated by the South. In equilibrium the South has lower wages than the North, so successful imitators in the South displace Northern innovators from the international market. The main difference between these models and the one I present here is that they assume that the South has free and immediate access to the new goods introduced in the North. Thus, except for the R&D sector, productivity is the same in both regions; wages are lower in the South only because the final good is assumed to be nontradable. [4]

Another model related to this paper is Barro and Sala-i-Martin (1995), who construct a model of technology adoption in which North grows by introducing new varieties of equipment goods, as in Romer (1990), while South grows by adapting the designs for those equipment goods to its local conditions. As in Parente and Prescott (1994), they assume that the cost of technology adoption increases as countries get closer to the technology frontier. Thus, all countries grow at the same rate in the long run, with policies that hinder technology adoption having effects only on a country's income relative to North. This feature is also present in a model developed by Eaton and Kortum (1994), which is closer to the present paper in that it considers technology adoption in the context of a quality-ladder model of growth. The main difference between this paper and the papers by Barro and Sala-i-Martin and Eaton and Kortum is that I emphasize the role of trade in the process of technology adoption whereas these authors assume that inputs are nontradable.

Lee (1995) presents a two-sector endogenous growth model (adapted from Rebelo, 1991) in which the price of equipment relative to consumption falls over time. He shows that an LDC can accelerate growth by specializing in consumption goods and importing equipment from more advanced countries. A tariff retards development by restricting this kind of trade. The present paper extends this previous work by assuming that using advanced equipment goods entails adoption costs and showing that in the presence of such costs trade barriers have magnified effects on the relative price of equipment (because of their impact on mark-ups) and on steady-state income per capita (because of their impact on mark-ups and on the technology gap).

Finally, Jovanovic and Rob (1996) have independently derived a model that generates similar results to the ones I derive in this paper. They assume that firms that buy high quality equipment must discard their old machines, in effect introducing a cost of technology adoption. A higher price of equipment (say, because of a tariff on imported machines) makes firms wait longer before upgrading their equipment, thus leading to a higher technology gap in steady state. There are two important differences be-

[4] If the final good was tradable then the South could specialize in the final good (if it is not to large), and the wage in the South would be the same as in the North. The final good being nontradable is of course very natural when innovation entails the introduction of new consumer goods rather than inputs; in this case the final good is simply utility.

tween the two models. First, the model developed here generates the result that tariffs lead to higher mark-ups charged on equipment, thus providing a plausible explanation for the high relative equipment prices prevailing in poor countries. Second, since it is individual firms that choose whether to adopt advanced technologies in Jovanovic and Rob's model, the technology gap that arises under free trade is optimal. Thus, in contrast to the model I develop here, a small tariff has only a second order effect.

2 The Model

There are two countries, which I call North and South. Each economy is inhabited by a representative agent whose utility is given by:

$$\int_t^\infty e^{-\rho(s-t)} \ln(C(s))ds \tag{1}$$

where $C(s)$ denotes consumption at time s.

There is a single consumption good (chosen as the numeraire), which is produced using labor (L), human capital (H), structures (K_s), and a composite input made from equipment goods (Z), according to the following Cobb-Douglas production function:

$$y = Z^\alpha K_s^\beta H^\zeta L^\varphi \tag{2}$$

where $\alpha + \zeta + \beta + \varphi = 1$. The qualitative results of the model do not depend at all on having human capital and structures enter the production function for output; the same qualitative results hold with a production function such as $y = Z^\alpha L^{1-\alpha}$. I introduce human capital and structures for the calibration exercise of Section 4.

The composite input Z is made from a continuum of differentiated equipment goods of varying quality as in the quality-ladder model of Grossman and Helpman (1991):

$$Z = \exp[\int_0^1 \ln(\sum_m q_{mj} x_{mj})dj] \tag{3}$$

where q_{mj} is the quality of equipment good j of generation m and x_{mj} is the quantity used of that equipment good. It is assumed that $q_{mj} = \lambda^m$. That is, a equipment good of generation $m + 1$ is λ times more productive than a equipment good of generation m.

Equipment goods are made from "putty clay," and can be converted back to putty clay at no cost. This assumption significantly simplifies the model because it implies that firms that buy equipment goods do not have to consider whether they should wait until new higher-quality equipment goods are introduced; when new equipment goods are introduced they can simply convert their current equipment goods into putty clay, sell it and then buy the new equipment. Putty clay, structures and human capital are all accumulated with the same production function as the consumption good. Equipment goods, structures and human capital all depreciate at the same instantaneous rate, δ.

I assume that there is innovation only in North; South does not perform any innovation, but it can import the higher-quality equipment goods produced in North. To do so, however, it must first adapt these equipment goods to the local environment. Since this leads to a higher technology level (and higher productivity), I will refer to this activity as technology adoption. I focus here on the case in which South is small enough that it does not affect the rate of innovation in North.

Innovation is stochastic, as in Grossman and Helpman. Specifically, an R&D intensity of ι implies an arrival rate for innovations of ι. To obtain an R&D intensity of ι a firm must hire $a_R\iota$ units of labor in North. Technology adoption is also stochastic: a technology adoption intensity of ξ implies an arrival rate for technology adoptions of ξ. I assume that to obtain a technology adoption intensity of ξ a firm must hire $a_A\xi$ units of labor in North. Perhaps it would be more natural to assume that technology adoption required both units of labor in North and in South, but I adopt the extreme assumption that no labor in South is needed to simplify the model. All of the qualitative results and most of the quantitative results would continue to hold if I assumed that technology adoption also required hiring workers in South. I discuss this issue in footnotes following some of the results.

Two additional assumptions concerning technology adoption are made to simplify the analysis. First, a firm that succeeds in technology adoption for equipment good j effectively adopts the technology for all generations of equipment good j currently available in North.[5] Second, technology

[5]This assumption implies that technology adoption allows a firm to close all of the technology gap for a particular equipment good. None of the results would change if I assumed instead that technology adoption allowed closing only a fraction of the technology gap. What is important is that technology adoption leads to greater quality improvement

adoption cannot be targeted to a particular equipment good. Specifically, a firm that succeeds in technology adoption does so for equipment good j, where j is uniformly distributed over $[0,1]$. If firms could target their technology adoption to particular equipment goods then *all* technology adoption efforts would be directed to the equipment good with the highest technology gap. To avoid this extreme result I would have to abandon the assumption that technology adoption arrives according to a Poisson distribution, and this would significantly complicate the model. In any case, the assumption of no targeting of technology adoption can be justified loosely by arguing that firms in South do not have perfect information about the technology gap for particular inputs, since they do not know how appropriate the new equipment introduced in North is for the local conditions of South.

I now turn to the characterization of equilibrium in North and then to the corresponding analysis for South. I will suppress the index for time and the subscript for N and S unless needed to avoid confusion.

2.1 Steady-State Equilibrium in North

Since the South is assumed too small to have any impact on the steady state level of R&D, the determination of equilibrium in North is very similar to the analysis of Grossman and Helpman. I go through this analysis here briefly to introduce some notation and also because it makes it easier to understand the analysis of equilibrium for South.

In equilibrium, firms that hold patents for one of the most advanced equipment goods do not engage in R&D; only "outsiders" spend resources in innovation. Successful innovators sell their patents to equipment-good producing firms, which then transform putty clay into equipment goods embodying the new design to rent it out to final-good firms.[6] Equipment-good firms charge a markup of λ over their marginal cost of renting out equipment goods, completely displacing the firms that hold patents for equipment goods of inferior quality (i.e., there is limit pricing). The marginal cost of renting out equipment goods is the gross-of-depreciation interest rate, which is denoted by R. Letting r denote the real interest rate, R is

when the technology gap is larger.

[6]Perhaps a more natural interpretation is that equipment-good producing firms sell their equipment to final-good firms, rather than renting it out. These alternative interpretation is formally equivalent to the one adopted in the text.

equal to $r + \lambda$. Thus, the equilibrium rental rate for equipment goods is λR.

For future reference, it is important to determine the composite price of equipment in North, P_Z. This composite price can be obtained from the cost minimization of Z. This yields

$$P_Z = \frac{\exp \int_0^1 \ln \lambda R dj}{\lambda^{I_N(t)}} = R\lambda^{1-I_N} \tag{4}$$

I_N is a quality index of equipment goods in North and is given by:

$$I_N(t) = \int_0^1 \tilde{m}_N(j,t)dj \tag{5}$$

where $\tilde{m}_N(j,t)$ is the latest generation of equipment good j that has been invented in North at time t.

To determine the equilibrium steady state rate of innovation in North, I first determine the profits made by a firm holding a patent for the most advanced equipment good of a particular variety. Given the logarithmic specification for the technology in 3, expenditure by final-good producing firms is the same for all varieties of equipment goods and is equal to $P_Z Z$. Since industry leaders in North charge λR to rent their equipment goods, their instantaneous profits are given by:

$$\pi = \frac{P_Z Z}{\lambda R}(\lambda R - R) = P_Z Z(1 - 1/\lambda) \tag{6}$$

For future purposes it is important to express the term $P_Z Z$ as a function of the quality index of equipment goods in North, I_N. To do this, note that a share α of the value of output (i.e., the value of consumer goods, structures, human capital and putty clay) is spent on equipment goods. Since $a_{R}\iota$ units of labor are used for R&D then only $L - a_R\iota$ units of labor are left over to produce output. We must then have that: $\alpha Z^\alpha K_s^\beta H^\zeta (L - a_R\iota)^\varphi = P_Z Z$. Since in equilibrium the marginal product of structures and human capital must be equal to R, this implies

$$P_Z Z = \phi(L - a_R\iota){P_Z}^{-\theta} \tag{7}$$

where ϕ is some constant and $\theta \equiv \alpha/\varphi$.[7] Using this expression and 4 and 6 I get the following expression for profits:

$$\pi = \phi(L - a_R\iota)(\lambda R)^{-\theta}\lambda^{\theta I_N}(1 - 1/\lambda)$$

[7]Some algebra shows that the term ϕ is given by $(\alpha^{\alpha+\varphi}\beta^\beta\zeta^\zeta/R^{\beta+\zeta})^{1/\varphi}$.

A steady state rate of innovation of ι implies that $dI_N/dt = \iota$, which in turn implies that the term $\lambda^{\theta I_N}$ (and hence π) grows at rate $\theta\iota \ln \lambda$ in steady state.

Letting V denote the steady-state value of a patent for the most advanced equipment good of a particular variety, the no-arbitrage condition requires that

$$\pi + \dot{V} - \iota V = rV$$

Since profits grow at rate $\theta\iota \ln(\lambda)$, this no-arbitrage condition implies that $V = \frac{\pi}{r+\iota-\theta\iota\ln\lambda}$. Consumption also grows at rate $\theta\iota \ln(\lambda)$ in steady state, and since the preferences specified above imply that the rate of growth of consumption in steady state must equal $r - \rho$, then the following restriction must hold in steady state:

$$\theta\iota \ln(\lambda) = r - \rho \tag{8}$$

Plugging this into the formula for V above we get:

$$V = \frac{\pi}{\rho + \iota} \tag{9}$$

Assuming that idiosyncratic risk can be completely diversified, firms care only about expected returns from R&D. Therefore, the equilibrium condition for ι is that the cost of a unit of R&D equals the value of a new patent, that is, $V = a_R w$. The Cobb-Doublas production function ensures that the condition $\theta = \alpha/\varphi = P_Z Z/w(L - a_R\iota)$ always holds, and this condition implies that the wage equals $w = P_Z Z/\theta(L - a_R\iota)$. Using this expression and equations 6 and 9 in the equilibrium condition $V = a_R w$ and rearranging we finally get the steady-state equilibrium rate of innovation in North:

$$\iota = \frac{\theta(1 - 1/\lambda)(L/a_R) - \rho}{1 + \theta(1 - 1/\lambda)}$$

Of course, this expression gives the steady-state rate of innovation as long as it is positive. If it is negative, then there is no innovation in steady state.

To determine output in steady state I use the fact that a share α of output is paid on renting equipment, which implies $\alpha y = P_Z Z$. Together with expression 7 this implies

$$y = (\phi/\alpha)(L - a_R\iota){P_Z}^{-\theta}$$

Thus, since P_Z falls at the rate $\iota \ln(\lambda)$, output grows at rate $\theta\iota \ln(\lambda)$ in steady state. I now turn to the equilibrium analysis for South.

2.2 Steady-State Equilibrium in South

The determination of the equilibrium rate of technology adoption in South is similar to the analysis above, except that here the mark-up charged by an industry leader is not fixed at $\lambda - 1$ but rather depends on the "gap" between the quality of equipment sold by the leader and its most advanced competitor in South. As we will see, this gap varies across equipment goods, leading to a whole distribution of mark-ups charged in South.

To determine this distribution of mark-ups in South we need some additional notation. Let $\tilde{m}_S(j,t)$ denote the latest generation of equipment good j available in South and let $\gamma(j,t) \equiv \tilde{m}_N(j,t) - \tilde{m}_S(j,t)$ denote the gap between the latest generation of equipment good j in North and South. I refer to this gap as the *technology gap*. Let $g^T(i,t)$ be the proportion of equipment goods for which the technology gap is equal to i at time t. Given a constant aggregate level of innovation ι in North and technology adoption ξ in South, the distribution $g^T(i,t)$ converges to the distribution $g(i) \equiv \frac{\xi}{\xi+\iota}\left(\frac{\iota}{\xi+\iota}\right)^i$. Letting $\Gamma(t) \equiv \sum_{i=0}^{\infty} i g^T(i,t)$ represent the average technology gap at time t, and letting γ denote the average technology gap in steady state, we have

$$\gamma \equiv \lim_{t\to\infty} \Gamma(t) = \sum_{i=0}^{\infty} i g(i) = \frac{\iota}{\xi} \tag{10}$$

When a Southern firm succeeds in technology adoption for equipment good j, the rate at which this firm will rent equipment goods to final-good firms in South depends on the gap between the generation of its equipment good and the generation of the most advanced equipment good of the same variety currently available in South. I refer to this gap as the *domestic gap*, to differentiate it from the *technology gap* between the highest quality of an equipment good available in South and North. (Note for comparison that the domestic gap for any equipment good in North is always 1.) Both the domestic gap and the technology gap will vary across equipment goods, as illustrated in Figure 2.

If the technology gap for a particular equipment good is i at the moment of technology adoption for that equipment good then the domestic gap will be i until the next technology adoption. An example may help to illustrate this idea. Consider a particular equipment good $\hat{j}$ for which the technology gap at time t_0 is 2 (see Figure 3). Imagine that the next technology adoption for this equipment good occurs at time t_1; the technology gap becomes 0 and the domestic gap becomes 2 at time t_1. If there is an innovation at time t_2 then $\tilde{m}_N(\hat{\jmath},.)$ increases by one at time t_2, leading to a technology gap of 1 for equipment good $\hat{\jmath}$ (the domestic gap is not affected). If the next technology adoption for equipment good $\hat{\jmath}$ occurs at time t_3 (and if no innovation occurs between t_2 and t_3) then again the technology gap becomes 0 and the domestic gap now becomes 1.

To determine the rental rate charged for an equipment good whose domestic gap is i I follow Grossman and Helpman in assuming that firms engage in price competition. This implies that a Southern firm that succeeds in technology adoption will practice a form of limit pricing and drive the firm that previously adopted technology for this equipment good out of the market. The concept of limit pricing is not as clear in the context of technology adoption, however, because Southern firms are buying their capital from Northern firms, so the game involves more than the usual two players. To formalize the concept of limit pricing in the context of technology adoption, consider a game in which Northern firms move first with a simultaneous announcement of the rate at which they will rent equipment goods to Southern firms and then Southern firm simultaneously decide from which Northern firm to rent equipment goods, how much to rent, and the rental rate they will charge in the domestic Southern market. In Appendix A I show that the most reasonable subgame-perfect equilibrium of this game entails the leader firms in South renting the most advanced gneration of equipment goods for which they have adopted technology at rate $\tau R\lambda$ and charging a domestic rate of $\tau R\lambda^{v(i)}$, where $v(i) = i$ for $i \geq 1$ and $v(0) = 1$, where i is the domestic gap and where $\tau - 1$ is the tariff imposed by South on all imports.[8] [9] As with limit pricing, follower firms in South are completely displaced from the domestic market in South.

To determine the steady-state equilibrium rate of technology adoption, I proceed as in the previous section. I first derive profits and the value

[8]The reader may wonder why South would impose a tariff on inputs if there are no domestic producers of such inputs to protect. A reasonable explanation for such tariffs, which are significant in several LDCs, is that governments there have a difficult time raising revenue through other means; imports represent a relatively easy way of financing public expenditures for these countries.

[9]The reader should keep in mind that although I consider a market in which equipment-good producers rent out their equipment to final-good firms, a more natural — but formally equivalent— interpretation is that they sell the equipment. The interpration of the effect of the tariff on equipment prices in South becomes more clear under this alternative interpretation.

of a firm that has succeeded in technology adoption. The condition that this value is equal to the cost of technology adoption then determines the steady-state equilibrium.

Profits made by a firm that succeeds in technology adoption for an equipment good with domestic gap i are given by

$$\pi^i = \frac{P_Z Z}{\tau\lambda^{v(i)}R}\left(\tau\lambda^{v(i)}R - \tau\lambda R\right) = P_Z Z(1-\lambda^{1-v(i)}) \tag{11}$$

Let V^i denote the steady-state value of a firm that has adopted technology for an equipment good whose technology gap is equal to i at the moment of adoption. Such a firm makes profits equal to π^i, since the domestic gap for the equipment good it adopted is i. Assuming that South is open to capital flows from and to North so that the domestic interest rate is equal to r, the no-arbitrage condition requires that

$$\pi^i + \dot{V}^i - \xi V^i = rV^i \tag{12}$$

Since $P_Z Z$ grows at rate $\theta\iota\ln\lambda$ in steady state (see below), then π^i must also grow at this rate in steady state. Together with 8, 11 and 12 this implies that:

$$V^i = \frac{P_Z Z(1-\lambda^{1-v(i)})}{\rho+\xi} \tag{13}$$

Since individuals can diversify away all idiosyncratic risk, then firms care only about the expected returns from technology adoption. To calculate the expected value of V^i, recall that the distribution of the technology gap in steady state is given by $g(i)$. Thus, the value of firm that has been successful in technology adoption but does not yet know for which equipment good is $V \equiv \sum_{i=0}^{\infty} V^i g(i)$. From 13 we then get:

$$V = \left(\frac{P_Z Z}{\rho+\xi}\right) m(\gamma) \tag{14}$$

where $m(\gamma)$ is the average mark up in steady state, and is equal to

$$m(\gamma) \equiv \sum_{i=0}^{\infty}(1-\lambda^{1-v(i)})g(i) = \frac{\gamma^2(\lambda-1)}{(1+\gamma)(\lambda+\gamma(\lambda-1))}$$

As one would expect, the average mark-up is increasing in the average technology gap, γ.

It is now necessary to determine the aggregate equilibrium expenditure on Z, $P_Z Z$. Letting $i(j)$ denote the domestic gap for equipment good j, minimization of the cost of a unit of Z in South yields

$$P_Z = \frac{\exp \int_0^1 \ln(\tau R \lambda^{v(i(j))}) dj}{\lambda^{I_S(t)}} = \tau R \lambda^{\eta(\gamma) - I_S} \tag{15}$$

where $\eta(\gamma) \equiv \sum_{i=0}^{\infty} v(i) g(i) = \gamma + \frac{1}{1+\gamma}$ and I_S is the quality index of equipment goods available in South and is given by $I_S(t) = \int_0^1 \tilde{m}_S(j,t) dj = I_N(t) - \gamma$. As in the previous section it an be shown that $P_Z Z = \phi L {P_Z}^{-\theta}$. Plugging in for P_Z from expression 15 we get

$$P_Z Z = \phi L (\tau R)^{-\theta} \lambda^{-\theta(\gamma + \eta(\gamma) - I_N)} \tag{16}$$

Plugging this into 14 finally yields an expression for V as a function of the average technology gap:

$$V = \lambda^{\theta I_N} \left(\frac{\phi L (\tau R)^{-\theta} \lambda^{-\theta[\gamma + \eta(\gamma)]}}{\rho + \xi} \right) m(\gamma) \tag{17}$$

If there is positive positive technology adoption in steady state then V must be equal to the cost of technology adoption, which is given by $a_A w_N$ (w_N denotes the wage in North). Using the results of the previous section and some algebra one gets:

$$w_N = (\phi/\theta)(\lambda R)^{-\theta} \lambda^{\theta I_N} \tag{18}$$

Using this result, equation 17 and some algebra I finally arrive at the steady-state equilibrium condition for γ (and indirectly for ξ, since $\xi = \iota/\gamma$):

$$\left(\frac{1}{\rho + \iota/\gamma} \right) m(\gamma) = \frac{a_A (\tau/\lambda)^{\theta} \lambda^{\theta[\gamma + \eta(\gamma)]}}{\theta L} \tag{19}$$

The first term of the LHS is one over the effective discount rate for technology adopters in South, while the second term is the average mark-up charged on equipment goods. The LHS of 19, which is drawn as curve VV in Figure 4, then measures the expected present value per unit of demand (i.e., per unit of $P_Z Z$) of a firm that has been successful in adopting technology but does not yet know for which particular equipment good. Curve VV

is increasing in γ, because a larger average technology gap also implies a larger average domestic gap and hence higher mark-ups.

The RHS of 19, which is drawn as curve CC in Figure 4, measures the cost of technology adoption per unit of demand. Curve CC is also increasing in γ. There are two reasons for this. First, an increase in the average technology gap makes South less productive, and this leads to a lower demand for equipment goods. Second, an increase in γ also implies an increase in the average domestic gap, which implies larger mark-ups charged on equipment goods in South and a lower aggregate demand for Z.

To determine the points of intersection between curves VV and CC, note first that at $\gamma = 0$ the curve VV crosses the origin, while the curve CC attains a level of $a_A\tau^\theta/\theta L > 0$. As $\gamma \to \infty$, on the other hand, the LHS of 19 converges while the RHS grows without bound. Therefore, for $a_A\tau^\theta/\theta L$ sufficiently small, curve VV crosses curve CC twice, first from below and then from above (see Figure 4).[10] This gives two steady-state equilibrium levels for γ. In Appendix B I analyze the out of steady-state dynamics of the model, showing that — for the parameters used in the calibration of the model in Section 4— the steady state with the lower level of γ (labeled $\hat{\gamma}$ in Figure 4) is stable whereas the steady state with the higher level of γ is unstable. I also show in Appendix B that as long as $\hat{\gamma} < \frac{1}{\theta \ln(\lambda)}$ (a condition that is always satisfied for the parameters used in Section 4) then the steady state equilibrium with the lower level of γ is isolated, in the sense that if the economy starts there then the only equilibrium is to remain there. I therefore choose the steady state with $\gamma = \hat{\gamma}$ as the basis for the subsequent analysis.

The equilibrium steady-state technology gap $\hat{\gamma}$ is increasing in the parameter a_A and the tariff τ and decreasing in the size of the market, represented here by L. This last result is analogous to the result that larger markets lead to more innovation in models of R&D.

To understand how trade policy affects the steady-state technology gap in South, note that an increase in τ increases the cost of technology adoption per unit of demand (the RHS of 19). As shown in Figure 4, this leads to an increase in the steady state level of γ. Intuitively, a tariff leads to a contraction of demand for equipment goods in South, reducing profits for

[10] If $a_A\tau^\theta/\theta L$ is too high then curve VV would be everywhere below curve CC, and there would be no technology adoption in equilibrium. The average technology gap $\Gamma(t)$ would then grow without bound.

Southern firms that rent out such equipment goods and making technology adoption less attractive. The reduction in technology adoption leads to a larger technology gap between North and South, increasing the average domestic gap. This allows successful technology adopters to charge higher mark-ups, restoring the equality between the expected value of success in technology adoption and its cost.[11]

3 Welfare Analysis

What are the welfare implications of the decline in technology adoption caused by tariffs or barriers to technology adoption? The answer to this question is not straightforward, because — just as with models of innovation— there are positive and negative externalities associated with technology adoption. If the negative externalities were to dominate the positive externalities at the steady-state equilibrium, then a policy that leads to a reduction in technology adoption could actually improve welfare. To consider this possibility, I now examine whether the rate of technology adoption in steady-state equilibrium is *locally* too low or too high compared to the socially optimal rate of technology adoption.

What are the positive and negative externalities associated with technology adoption? First, there is the standard positive consumption externality present in models of innovation, which arises here from the fact that entrepreneurs do not take into account the benefit derived by final good producers (and therefore by consumers of the final good) from using inputs of higher quality. I refer to this externality as the *direct-productivity effect.* Second, there is an additional positive externality that arises here from the pricing distortion caused by the mark-ups charged on equipment goods. More technology adoption causes the average technology gap (and

[11]It is interesting to see how the results would change if technology adoption required only South labor. In this case, the equilibrium condition would be $V = a_A w_S$, where w_S denotes the wage in South. V is still equal to $m(\gamma)P_Z Z/(\rho+\xi)$ (see equation 14). The wage in South is obtained by noting that the condition $\theta = \alpha/\varphi = P_Z Z/w_S(L - a_A\xi)$ always holds, and this condition implies $w_S = P_Z Z/\theta(L - a_A\xi)$. The steady-state equilibrium would then be determined by the condition $m(\gamma)/(\rho + \xi) = a_A/\theta(L - a_A\xi)$. We see here that a tariff has no impact on the equilibrium rate of technology adoption. The reason is that although a tariff lowers the rewards from technology adoption (it lowers V by decreasing $P_Z Z$), a tariff decreases the cost of technology adoption in exactly the same proportion (it lowers w_S by decreasing $P_Z Z$).

domestic gap) to fall, thereby causing a reduction in the pricing distortion associated with the mark ups charged on equipment goods. This involves a positive externality which I refer to as the *price-distortion externality.* Finally, there is the negative externality that arises from the usual *profit-stealing effect* present in models of innovation (see Grossman and Helpman, 1992).

To see whether the negative or positive externalities dominate, I follow Grossman and Helpman in considering a small perturbation consisting of a discrete increase in technology-adoption efforts at time $t = 0$. From then on I assume that $\xi = \hat{\xi}$. Since South is completely open to capital flows, then it is enough to compare the effect of this small perturbation on the present value of the future stream of net income (defined as the value of production minus the cost of renting equipment goods from North minus the cost of technology adoption) with the cost in terms of foregone consumption at $t = 0$.

The first step is to see how the distribution of the technology gap and the domestic gap are affected by the discrete increase in the intensity of technology adoption at time $t = 0$. To do so, recall that $g^T(i,t)$ denotes the proportion of capital-good varieties for which the technology gap is equal to i at time t, and let $g^D(i,t)$ denote the corresponding concept for the domestic gap. It was established above that in steady state,

$$g^T(i,t) = g^D(i,t) = g(i) \equiv \frac{\hat{\xi}}{\hat{\xi} + \iota}\left(\frac{\iota}{\hat{\xi} + \iota}\right)^i$$

At time $t = 0$ there is a discrete increase in the intensity of technology adoption by Δ. This implies that at that time, there is a discrete probability Δ of technology adoption for each equipment good.[12] Therefore, assuming that the system was in steady state up to $t = 0$, then just after the perturbation we have

$$g^T(0,0) = g(0) + \Delta\left(\frac{\iota}{\iota + \hat{\xi}}\right)$$

and

$$g^T(i,0) = (1 - \Delta)g(i)$$

[12] By discrete increase in technology adoption at time t=0 I actually mean that $\xi(t) = \hat{\xi} + \Delta\delta(t)$, where $\delta(t)$ is Dirac's delta function, characterized by the fact that $\delta(t) = 0$ for all $t \neq 0$ and $\int_{-\infty}^{\infty} \delta(t)dt = 1$.

for $i > 0$.[13] $g^D(i,0)$ is not affected by the perturbation at time $t = 0$, a result that can be derived from the fact that up to time $t = 0$ we had $g^T(i,t) = g^D(i,t)$. Since technology adoption goes back to $\hat{\xi}$ after time $t = 0$, both $g^T(i,t)$ and $g^D(i,t)$ eventually converge back to $g(i)$. The law of motion for $g^T(i,t)$ and $g^D(i,t)$ is given by the following equations:

$$\begin{aligned} \dot{g}^T(0,t) &= \hat{\xi}(1 - g^T(0,t)) - \iota g^T(0,t) \\ \dot{g}^T(i,t) &= \iota g^T(i-1,t) - (\hat{\xi} + \iota) g^T(i,t) \\ \dot{g}^D(i,t) &= \hat{\xi}(g^T(i,t) - g^D(i,t)) \end{aligned} \tag{20}$$

The next step is to derive an expression for net income that is valid even when the system is out of steady state. Let J denote net income (in terms of the final good) and let w_S denote the wage in South. Net income in terms of labor is simply $Q = J/w_S$, and this must be equal to total earnings by workers, L, plus total profits in terms of labor, Π, minus the cost of technology adoption in terms of labor, $a_A w_N \hat{\xi}/w_S = a_A \sigma \lambda^{\theta I_N} \hat{\xi}/w_S$, where $\sigma \equiv (\phi/\theta)(\lambda R)^{-\theta}$ (using 18). That is (from here on I drop the subscript S from w_S),

$$Q = L + \Pi - a_A \sigma \lambda^{\theta I_N} \hat{\xi}/w \tag{21}$$

Noting that $J = Qw$, the present value of the stream of net income as a function of the technology-adoption shock can be written as follows

$$\Upsilon(\Delta) \equiv \int_0^\infty e^{-rt} Q(t) w(t) dt$$

The cost of the discrete technology adoption by Δ at time $t = 0$ is $a_A \sigma \lambda^{\theta I_N(0)} \Delta$. Therefore, the net welfare effect of a small technology adoption shock is determined by the sign of

$$\begin{aligned} \Upsilon'(0) - a_A \sigma \lambda^{\theta I_N(0)} &= \int_0^\infty e^{-rt} w^{ss}(t) \frac{dQ(t)}{d\Delta}|_{\Delta=0} dt \\ &+ \int_0^\infty e^{-rt} Q^{ss} \frac{dw(t)}{d\Delta}|_{\Delta=0} dt - a_A \sigma \lambda^{\theta I_N(0)} \end{aligned}$$

where a superscript ss implies that the variable is evaluated at steady state. Using 21 we get after some manipulation (see Appendix C) that:

$$\Upsilon'(0) - a_A \sigma \lambda^{\theta I_N(0)}$$

[13] The formal proof of this statement is available upon request from the author.

$$= \lambda^{\theta I_N(0)} N \left[-E \int_0^\infty e^{-\rho t} \frac{d\Gamma(t)}{d\Delta}|_{\Delta=0} dt - E \int_0^\infty e^{-\rho t} \frac{d\Omega(t)}{d\Delta}|_{\Delta=0} dt \right.$$
$$\left. +(1/\theta L) \int_0^\infty e^{-\rho t} \frac{d\Pi(t)}{d\Delta}|_{\Delta=0} dt - m(\hat{\gamma})/(\rho + \hat{\xi}) \right] \quad (22)$$

where N and E are positive constants defined in Appendix C. There are four terms on the parenthesis of the RHS of this expression. The first term clearly captures the impact of the technology-adoption shock on the technology gap and corresponds to the direct-productivity effect. The second term captures the impact of the shock on the average mark-up and corresponds to the price-distortion effect. The third term captures the change in total profits caused by the shock, including the profits made by whomever financed the technology-adoption shock, while the fourth term captures the cost of this shock. Since the system starts at equilibrium, the cost of the technology adoption shock is equal to the discounted profits made from it. Thus, the third plus the fourth terms capture the net impact of the shock on the profits of people other than the ones financing the shock. This is precisely the profit-stealing effect.

Surprisingly, as shown in Appendix C, the expression above turns out to be always positive. This implies that, starting at the steady-state equilibrium, the positive externalities associated with the direct-productivity effect and price-distortion effect always outweigh the negative externality associated with the profit-stealing effect. The following proposition summarizes this result:

Proposition 1 *Starting at the steady-state equilibrium, a small temporary increase in technology adoption generates an increase in social welfare.*

This proposition does not necessarily implies that a policy that decreases the steady state rate of technology adoption improves welfare; it only tells us that *locally* there is too little technology adoption. This is useful, however, because it will help us to determine unambiguously the welfare impact of a small increase in barriers to trade or technology adoption. But before looking at this it is important to comment on Proposition 1 itself.

To understand Proposition 1, it may help to consider what happens if we change the original Grossman-Helpman quality-ladder model by assuming that innovation entails catching up to a quality frontier that improves exogenously. In this modified model innovation is very similar to technology adoption as modeled in the present paper, and it can be shown that a result equivalent to Proposition 1 is obtained: the steady-state intensity of innovation is *locally* too low compared to the optimal rate of innovation. Again, the result is due to the fact that, starting at the steady-state equilibrium, the direct-productivity and price-distortion effects dominate the profit-stealing effect (see Rodríguez-Clare, 1996).

Proposition 1 implies that a small temporary decline in technology adoption decreases welfare, so at least intuitively one would expect the sustained fall in technology adoption caused by a small tariff increase to also decrease welfare. This intuition is valid *as long* as the path followed by the rate of technology adoption ξ after the tariff increase satisfies the restriction $\int_0^\infty e^{-\rho t}\xi(t)dt > \hat{\xi}/\rho$ (see Appendix D). This leads directly to the following proposition, proved in Appendix D:

Proposition 2 *Starting from steady state, and assuming that*

$$\int_0^\infty e^{-\rho t}\left(\frac{\partial \xi_t}{\partial \tau}|_{\tau=\tau_0}\right)dt < \hat{\xi}/\rho$$

a small tariff increase from τ_0 decreases social welfare. Similarly, if

$$\int_0^\infty e^{-\rho t}\left(\frac{\partial \xi_t}{\partial a_A}|_{a_A=a_{A0}}\right)dt < \hat{\xi}/\rho$$

then starting at steady state, a small increase in a_A from a_{A0} decreases social welfare.

To complete this result, the assumptions $\int_0^\infty e^{-\rho t}\left(\frac{\partial \xi_t}{\partial \tau}|_{\tau=\tau_0}\right)dt < \hat{\xi}/\rho$ and $\int_0^\infty e^{-\rho t}\left(\frac{\partial \xi_t}{\partial a_A}|_{a_A=a_{A0}}\right)dt < \hat{\xi}/\rho$ must be verified to hold. This is not necessarily the case because, although the steady state rate of technology adoption falls as a result of an increase in τ or a_A, it may be that the path of ξ from one steady state to the next entails a long period of time for which ξ is higher than $\hat{\xi}$. Moreover, for several numerical simulations I have performed with the parameters used in the calibration of Section 4, it turns out that $\xi(t)$ goes to zero right after the policy change and remains at zero for a certain period of time, after which it jumps to a level *higher* than $\hat{\xi}$. Figure 5 illustrates the path of $\xi(t)$ after a small increase in τ or a_A.[14] The condition of Proposition 3 is then not easy to verify analytically,

[14]The reason why technology adoption goes to zero right after the policy change is

but this condition has been satisfied for all the numerical examples I have considered.[15]

4 Calibration of the Model

In this section I calibrate the model to determine the quantitative importance of the negative impact of barriers to trade and technology adoption on income per capita through its effect on the rate of technology adoption. For the parameters of the production function I could choose $\alpha = 1/6$, $\beta = 1/6$, $\zeta = 1/3$, $\varphi = 1/3$. This would imply a one third share of income for physical capital (both equipment goods and structures) and two thirds for labor, as is the case in the United States.[16] This choice of parameters would imply that $\theta = \alpha/\varphi = 1/2$. To determine the implications of this value of θ, recall that the annual rate of growth of output per worker is given by $\theta\iota\ln(\lambda)$, where $\iota\ln(\lambda)$ represents the annual rate of quality improvement for equipment. Using Gordon's (1990) estimate of an annual rate of quality improvement for producers durable equipment of 2.9% for the 1947-1983 period, one obtains that $\iota\ln(\lambda) = 0.029$.[17] A value of one half for θ then implies an annual rate of growth of output per worker of

that the average technology gap does not decline immediately. Thus, the cost of technology adoption increases while its benefits remain unchanged immediately after the policy change. A zero rate of technology adoption leads to a gradually increasing average technology gap, which eventually restores the equality between cost and benefits to technology adoption, leading to a positive rate of technology adoption.

[15] I have done this for three different values of $b \equiv (\phi/(\tau R)^{\theta})L/a_A$, $b = 0.5$, $b = 1$, $b = 2$, in each case considering a reduction of b by 5%.

[16] This is only approximately true, because we should also take into account income from the R&D sector. Since this is a small part of total income, the statement in the text is approximately correct.

[17] Although the model presented above assumes that all technological change leads to *quality improvement* in capital goods, it is straightforward to extend the model to include also technological change that leads to *cost reductions* in capital goods. The model remains basically unchanged, the only difference being that now $\iota\ln(\lambda)$ should be interpreted as the rate of decline in the quality-adjusted price of equipment relative to consumption. The above analysis is still quantitatively valid, however, because the rate of decline in the quality-adjusted relative price of equipment (measured from Gordon's equipment price series and the deflator for consumer nondurables and nonhousing services) is 2.9%, which is basically the same as the rate of quality improvement for equipment during those years. That is, the quality-unadjusted relative price of equipment does not experience a decline from 1946 to 1983.

$0.5 * 0.029 = 0.0145$, or 1.45%.[18] This is very close to the actual rate of growth of GDP per worker of 1.5% from 1950 to 1990 in the U.S. (according to the Summers and Heston Mark 5.6 data set). I deviate slightly from the above values for α, β, ζ, and φ to get θ equal to 0.52, which then implies a rate of growth of output per worker of 1.5%, exactly equal to the U. S. rate of growth during the 1950-90 period.

Now I turn to the determination of the remaining parameters. To determine values for r and ρ, I use the fact that consumption (and hence GDP per capita over the long run) must grow at the rate $r - \rho$. Using a value for the risk-free real interest rate in the U.S. of 4 percent, and assuming that the rate of growth in consumption equals the rate of growth in output per worker in the US during the 1950-90 period, this implies that ρ must be equal to 2.5. For the depreciation parameter, δ, I follow standard practice and assume that the rate of depreciation is 6 percent a year.

Since I do not have any estimates for the parameter λ, I perform simulations with three different values for λ: a low value of 1.1, an intermediate value of 1.4, and a high value of 1.7. For each one of these values of λ I determine ι using Gordon's estimate for the rate of quality improvement in equipment, which implies the restriction: $\iota \ln(\lambda) = 0.029$.

The parameter a_A remains to be determined. As we will see, the effect of barriers to trade or technology adoption depend on the rate of technology adoption that would obtain in the absence of those barriers. This rate depends on the parameter $\hat{a}_A$, which denotes the level of a_A in a country where the are no barriers to technology adoption. Since I do not have estimates of $\hat{a}_A$, I consider the effects of trade and technology adoption barriers for various possible levels of $\hat{a}_A$.

[18] The annual rate of quality improvement calculated by Gordon is actually for *new* equipment goods, whereas this paper's assumption that equipment goods can be converted into putty clay at no cost implies that $\iota \ln(\lambda)$ is the annual rate of quality improvement of *all* equipment. Note, however, that the rate of growth of output does not depend on whether quality improvements affect all equipment or only new equipment, so the procedure followed in the text is correct. Moreover, since all the results below relate to steady state values, this distinction does not matter for the results.

4.1 The impact of barriers to trade and technology adoption

It is now possible to determine the quantitative importance of the effect of tariffs or barriers to technology adoption on relative income levels through their impact on technology adoption. It turns out that the quantitative implications of the model do not vary significantly with the value of the parameter λ used. Accordingly, in the results below I only report the findings obtained using the intermediate level of λ (i.e., $\lambda = 1.4$).

Let $\mu \equiv a_A/\hat{a}_A - 1$ denote the percentage increase in the cost of technology adoption resulting from various policies. Table 1 presents the first set of results showing the relative income level under different values for τ and μ for a country whose output per worker under $\tau = 1$ and $a_A = \hat{a}_A$ would be 75 percent of the U.S. level (given that all the other parameters are already determined, this entails choosing $\hat{a}_A/L$ in such a way that the steady state technology gap implies a relative income level of 0.75). Table 2 presents the percentage fall in relative income caused by a 10 percent tariff or by barriers to technology adoption that cause a 10 percent raise in the cost of technology adoption (i.e., $\mu = 0.1$) for values of $\hat{a}_A$ that yield various levels of relative income when $\tau = 1$ and $a_A = \hat{a}_A$. These tables show that the effect of tariffs or barriers to technology adoption on output per worker is potentially important. For instance, for a country whose relative income level would be 0.55 under no barriers to trade or technology adoption, a 10 percent tariff leads to a decline in relative income of almost 8.5 percent, while policies that increase the cost of technology adoption by 10 percent lead to a reduction in relative income of almost 8.0 percent.

A tariff decreases steady-state relative income by increasing the price of equipment goods and depressing accumulation of structures and human capital. The price of equipment goods increases because of the impact of the tariff on the rate of technology adoption but also because of the direct effect of the tariff. Thus, even if the tariff had no effect on technology adoption, it would still have an effect on relative income levels. Table 3 shows the decomposition of the total effect of the tariff into its direct effect and its effect through its impact on technology adoption. The table shows that when free trade relative income is high the technology adoption effect is small; almost all of the impact of the tariff on relative income arises because of the direct effect of the tariff on prices of equipment goods. For low relative income levels, however, the technology adoption effect becomes significant.

4.2 Implications for Relative Income Levels

In this subsection I use the calibrated model to see how much of the large international dispersion in output per worker levels can be explained as a consequence of different rates of technology adoption. To do so, I now interpret "North" as the United States and I allow for several "South" or developing countries (since I assumed that South was small this introduces no changes in the model as long as the measure of South countries remains equal to zero).

Let $y_{rel,i}$ denote country i's steady-state output per worker relative to the U. S., and let $p_i \equiv P_Z^i / P_Z^{US}$ denote the quality-adjusted price of equipment relative to consumption for country i relative to the U. S. It can be shown that $y_{rel,i} = p_i^{-\theta} = p_i^{-0.52}$. For a country with a relative income of one fourth ($y_{rel,i} = 1/4$) this implies that $p_i = 4^{1/0.52} = 14.4$, a price that is significantly higher than the relative equipment prices reported by Jones (1994) (see Figure 1).

One problem with this exercise is that the data assembled by Jones on the price of producers' durable equipment is not appropriately adjusted for quality, whereas the price index P_Z is obviously quality-adjusted.[19] To correct for this problem, note that whereas the quality-adjusted relative price of equipment for South relative to North is $P_Z^S / P_Z^N = \tau \lambda^{\eta(\gamma)+\gamma-1}$, the relative price that would be *measured* if no account is taken of differences in quality is:

$$\frac{P_{mZ}^S}{P_{mZ}^N} = \tau \lambda^{\eta(\gamma)-1}. \tag{23}$$

To determine an upper bound on the income differences that this model can account for, I make the extreme assumption that the data on equipment prices coming from the Summers and Heston benchmark studies do not control at all for quality. The data on equipment prices in Jones (1994) can then be taken as the empirical counterpart of P_{mZ}^S / P_{mN}^N for several

[19] The benchmark surveys behind the Summers and Heston data do try to control for differences in quality, but the problem is that there are several goods that are not found in some countries. Now, it is likely that after several quality improvements, a good no longer looks like the original good. There would then be many missing items in a country with a large technology gap, and the price index constructed with the data on prices for the available goods would not reflect the quality differences implicit in this gap.

"South" countries.[20] Using data for τ I can determine the corresponding γ from the equation above.[21] Using this and the formula $P_Z^S/P_Z^N = \tau\lambda^{\eta(\gamma)+\gamma-1}$ I can obtain from the equipment price data a modified price that is directly comparable to the model's P_Z^S/P_Z^N variable.

Table 4 reports the results of this exercise for all the countries included in the Summers and Heston study for which I have data on tariffs and on prices for equipment and which have a measured price of producer durables *higher* than that in the U.S.[22] The first three columns of Table 4 show data for relative income, measured relative equipment prices and tariffs. Using the method outlined above, this data can be used to generate the model's prediction for each country's γ, its quality-adjusted relative equipment price and its relative income level, which are shown in the next three columns of Table 4. Finally, the following column of Table 4 shows the model's implied number of "years behind the frontier" for each country. That is, it shows how many years ago the U.S. was using equipment of average quality equal to what a country uses in the present.[23] As an example, consider the case of Costa Rica. The model implies that it uses inputs of an average quality similar to what the U.S. was using 27 years before. This technology gap implies an average mark-up above the U.S. of $\lambda^{\eta(\gamma)-1} = 1.74$. The technology gap, the mark-up and the 16% tariff on equipment goods lead to a quality adjusted relative equipment price of 4.45, which translates into an implied relative income level of 0.46.

[20] A better approach would be to assume that the benchmark studies adjust for quality for all the goods that are found in a country, but that if the technology gap for a particular equipment good is higher than M then the good is reported missing. Data on the number of equipment goods missing in each country could then be used to estimate M and correct for quality in a less extreme way than done in the text. I do not follow this approach because I have not been able to get data on the number of equipment goods that were not found in different countries.

[21] τ is taken from Lee (1993), who put together data on tariff rates on imported intermediate goods and capital goods for 108 countries from various sources. One problem with this data is that it refers to several years during the 1980s and not to 1980 as the rest of the data that is used in the present paper. This does not represent a significant problem to the extent that tariff rates do not vary much over time.

[22] Since the U.S. is taken as the world's counterpart of the North country in our model, countries with a relative price of durables *lower* than in the U.S. do not fit the role of the South country in the model.

[23] To see how this number is obtained, recall that γ is the gap between the technology index of South and North (i.e., $I_S = I_N - \gamma$). Letting the present be $t = 0$, then using $\dot{I}_N = \iota$ we get $I_N(-\hat{t}) = I_N(0) - \iota\hat{t} = I_S(0)$, which implies $\hat{t} = \gamma/\iota$.

It is clear from Table 4 that —given the data available for equipment prices— the model cannot account for the large disparity in relative income levels seen in the data. The lowest relative income level predicted by the model is 0.27 for Peru, which has the highest quality-adjusted equipment price ($p_{peru} = 12.23$).[24] Thus, given measured equipment prices, the model cannot explain relative income levels of 1/4 or less.[25]

The last two columns of Table 4 report the ratio of equipment imports in 1980 to total income in that same year (GDP at current *international* prices) and the model's implied value for this ratio given observed equipment prices.[26] There are two interesting observations to point out here. First, actual equipment imports are generally lower than those implied by the model. This can be seen graphically in Figure 6. Second, running a regression of the ratio of equipment imports to GDP on the log of measured relative equipment prices relative to the U.S. (i.e., the variable P^S_{mZ}/P^N_{mN}) yields a coefficient of -0.036 with standard error of 0.009 (t-statistic of -3.8). Running the same regression but using the model's implied ratio of equipment imports to GDP yields a coefficient of -0.051 with standard error of 0.002. The hypothesis that these two coefficients are identical cannot be rejected at the 10% confidence level. Moreover, it is likely that measurement error biases the coefficient of the first regression downwards,

[24]Table 4 is constructed for $\lambda = 1.4$. I have done the same exercise for $\lambda = 1.1$ and for $\lambda = 1.7$ and the results do not change in any significantive way. For instance, the predicted relative income for Peru for $\lambda = 1.1$ is 0.3, whereas for $\lambda = 1.7$ it is 0.26.

[25]There is another reason why this model of technology adoption cannot explain very low income levels: when population is low, or barriers to technology adoption or trade are high, then the equilibrium rate of technology adoption becomes zero, implying an ever falling relative income level. One can show that there is no steady state equilibrium for the model if $(a_A/L)\tau^{0.52} > 0.67$. The steady-state technology gap for the case where $a_A(/L)\tau^{0.52} = 0.67$ is $\gamma = 3.51$ and the associated steady state relative income is $0.34/\tau^{0.52}$. Thus, for a 100 percent tariff relative income is 0.23. If technology adoption required South labor insteady of North labor, as assumed in the text, then there would always be a positive steady state rate of technology adoption (see the steady state equilibrium condition in footnote 11). In any case, modifying the model in this way does not appear relevant here because, as discussed in the text, it does not seem that countries have technology gaps larger than what the calibrated model allows.

[26]The model's implied equipment imports at time t are given by $\lambda(\delta Q(t) + \dot{Q}(t))$, where $Q(t)$ represents the total quantity of equipment used at time t and is given by $Q(t) = \int_0^1 \left(P_z Z/\tau R \lambda^{v(i(j))}\right) dj = \phi L(\tau R)^{-(\theta+1)} \left(\frac{1-m(\gamma)}{\lambda}\right) \lambda^{-\theta(\gamma+\eta(\gamma)-I_N)}$. Dividing by GDP and simplifying one gets that the value of equipment imports over GDP is given by $\alpha(\frac{R-\rho}{R}) \left(\frac{1-m(\gamma)}{\tau}\right)$.

making it more likely that these two coefficients are indeed equal. What I conclude from these two observations is that the model's assumption that South must import all the equipment it uses is not consistent with the data. Domestic production of equipment would obviously lead to lower imports of equipment relative to GDP. I discuss this possibility further in the last section.

4.3 Implications for Equipment Prices

It has been observed by Jones (1994) and De Long and Summers (1991) that equipment prices are inversely correlated with output per worker (see Figure 1). One could try to explain this observation by noting that the price of equipment in these previous studies is relative to consumption, which includes several non-tradables. Since equipment is tradable, this implies that part of the reason that relative equipment prices vary inversely with output per worker is the standard positive correlation between income per capita and the relative price of non-tradables versus tradables. This is certainly part of the explanation, but it is not the whole story, because the price of equipment relative to *tradables* also exhibits a negative correlation with income per capita. For instance, relative to the goods grouped under "clothing and footwear" in the United Nations ICP project, the price of producer durables was 2.34 times higher in 1975 for the poorest countries than for the United States. The corresponding value for the price of producer durables relative to "consumption" was 3.24 (see Kravis, Heston and Summers, 1982).

One could argue that this negative correlation between income per capita and equipment prices relative to other tradable goods is due to the existence of high tariffs on equipment in poor countries. But it is unlikely that poor countries have tariffs on equipment that are that much higher than the tariffs imposed on tradable goods such as clothing and footwear. The model developed in this paper provides an explanation that does not depend on high tariffs on equipment. In particular, the model implies that countries with a low rate of technology adoption will have a high measured price of equipment because the large average technology gap caused by the low rate of technology adoption allows successful technology adopters to charge high mark-ups on the sale of equipment.

To see this, consider a country with *no tariffs* and an average technology gap of $\gamma_i = 3.60$ (which implies a steady-state relative income level of

0.325). The model implies that the measured relative price of equipment would be 2.58 times the level observed in the United States (i.e., $P_Z^i/P_Z^{US} = 2.58$). Thus, the model can easily generate the international dispersion in measured equipment prices that is seen in the data.

I run a regression to check the consistency of the model's qualitative prediction that countries with higher tariffs and small populations have higher relative equipment prices. I included the average distance to the world's 20 major exporters of manufactures (taken from the Barro-Lee data set) in the regression, because it is likely that the cost of importing equipment goods increases with this measure of distance. The results are reported in Table 5. The three right-hand variables included all have the right signs and are significant at the 2.5% confidence level. Note that the scale effect implied by the model is not inconsistent with the data: just as the model implies, a larger scale, as measured by population, implies a lower price for equipment goods.

5 Final Remarks

This paper has constructed a model in which trade in equipment goods is central to the process of technology diffusion. Barriers to trade or technology adoption imposed in a developing country lead to a lower rate of technology adoption and a higher steady state technology gap. In turn, the higher technology gap implies a lower relative income level. The calibrated model revealed that these effects are significant, and that the model can account for differences in income per capita of up to a factor of 4. The model also provides an explanation for the fact that equipment prices are higher in poor countries.

The result that tariffs lead to a reduction in the rate of technology adoption is not limited to tariffs on equipment goods. A similar model can show that tariffs on final goods can also have a negative impact on technology adoption. The basic idea is that, if equipment goods are industry specific, then a larger industry will support more technology adoption, just as a larger market leads to a higher rate of innovation in models of R&D. Hence, by restricting specialization, barriers to trade (even in the form of tariffs on final goods) effectively decrease the scale of the market and reduce technology adoption. In other words, a tariff on final goods leads the economy to spread its resources more thinly over many sectors, making it less profitable to adapt foreign equipment goods for any particular industry.

An interesting extension of the model would be to consider the possibility of copying designs of equipment goods in South. If this was possible then at any moment there could be domestic firms producing equipment goods that compete against new foreign designs. Domestic pressures for protection could then lead to tariffs on equipment goods, slowing down technology adoption. The costs of a slower rate of technology adoption would be different than those considered in this paper, however, because now it would be accompanied by increased efforts to copy equipment good designs. Thus, the technology gap would likely increase by less as a consequence of a tariff, but there would be additional distortions arising from inefficient home production of low-quality equipment. This seems an interesting topic for future research.

6 Appendix A: Equilibrium of game between Southern and Northern firms

Consider a particular equipment good $\hat{j}$. At time t there are $\tilde{m}_N(\hat{j},t)$ generations of that equipment good $\hat{j}$ available in North. Denote the Northern firm that introduced generation $l \leq \tilde{m}_N(\hat{j},t)$ of equipment good $\hat{j}$ by N_l and denote the price offered by that firm to Southern firms by p_l. I first determine the equilibrium in the second stage of the game given these prices. Let $U = \{t_0, t_1, ...t_M\}$ be the set of times at which there was successful technology adoption for equipment good $\hat{j}$ and denote the Southern firm behind technology adoption at time $t_k \in U$ by $S(\hat{j}, t_k)$. Firm $S(\hat{j}, t_k)$ can rent equipment goods from Northern firms $l \leq \tilde{m}_N(\hat{j}, t_k)$, and it will buy only from the Northern firm for which the quality adjusted price p_l/λ^l is lowest (in case of equality I assume that the firm prefers the one with the highest quality). Let $\tilde{q}_k = \min\{p_l/\lambda^l \text{ for } l \leq \tilde{m}_N(\hat{j}, t_k)\}$ denote the minimum quality-adjusted price available to Souhern firm $S(\hat{j}, t_k)$ and let $\tilde{k} = \max\{\arg\min\{\tilde{q}_k, k \in \{0, 1, ...M\}\}\}$. $S(\hat{j}, t_{\tilde{k}})$ is the Southern firm that has access to the lowest quality adjusted price from Northern firms. In the competition among Southern firms, the only firm that will be willing to rent equipment good $\hat{j}$ at all from North will be firm $S(\hat{j}, t_{\tilde{k}})$, which will rent it from Northern firm $N_{l(\tilde{k})}$, where $l(k) = \max\left\{\arg\min\{p_l/\lambda^l \text{ for } l \leq \tilde{m}_N(\hat{j}, t_k)\}\right\}$. Firm $S(\hat{j}, t_{\tilde{k}})$ will then rent out equipment good $\hat{j}$ of generation $l(\tilde{k})$ at a quality-adjusted price just high enough that the firm with the second lowest quality-adjusted price will not be able to compete, that is a quality-adjusted price $q = \min\left\{\tau\tilde{q}_k, k \in \{0, 1, ..., M\}/\tilde{k}\right\}$.

I can now go back to the first stage and determine the equilibrium prices offered by Northern firms. It is easy to see that no Northern firm will want to charge a price higher than $R\lambda$, since the Northern firm with the just-inferior generation could then undercut its price and steal all possible Southern clients. Since nothing in the game pins down the price offered by Northern firms which in equilibrium do not rent out any capital, there is multiplicity of equilibria. One equilibrium entails $\tilde{q}_k = R\lambda^{1-\tilde{m}_N(\hat{j},t_k)}$. In this equilibrium we would have $\tilde{k} = M$ and consequently $q = \tau R\lambda^{1-\tilde{m}_N(\hat{j},t_{M-1})}$, which implies a rental rate of $\tau R\lambda^{1-\tilde{m}_N(\hat{j},t_{M-1})} * \lambda^{\tilde{m}_N(\hat{j},t_M)} = \tau R\lambda^{1+i}$ charged by the South leader, where $i = \tilde{m}_N(\hat{j}, t_M) - \tilde{m}_N(\hat{j}, t_{M-1})$ is the domestic gap for equipment good $\hat{j}$. Note, however, that if $i > 0$ (so that there has been at least one innovation between times t_{M-1} and t_M), then Northern firm $\tilde{m}_N(\hat{j}, t_{M-1})$ is not able to rent out any capital in this equilibrium. This firm could lower its price all the way down to its marginal cost R and still not be able to rent out any capital. Still, just as in the standard analysis for symmetric duopoly under Bertrand competition, it is reasonable to assume that such a firm lowers its price down to its own marginal cost. An equilibrium consistent with this behaviour entails $\tilde{q}_M = R\lambda^{1-\tilde{m}_N(\hat{j},t_M)}$ and $\tilde{q}_k = R\lambda^{\tilde{m}_N(\hat{j},t_k)}$ for $k < M$. In this equilibrium we would still have $\tilde{k} = M$ but now $q = \tau R\lambda^{-\tilde{m}_N(\hat{j},t_{M-1})}$, which implies a rental rate of $\tau R\lambda^{-\tilde{m}_N(\hat{j},t_{M-1})} * \lambda^{\tilde{m}_N(\hat{j},t_M)} = \tau R\lambda^i$ charged by the South leader as long as $i > 0$. If $i = 0$ then the argument here does not apply, since generation $\tilde{m}_N(\hat{j}, t_M)$ is the same as generation $\tilde{m}_N(\hat{j}, t_{M-1})$, implying that $N_{l(M)} = N_{l(M-1)}$. Thus, for $i = 0$, the price charged in South is $\tau R\lambda$, finally proving the result in the text.

7 Appendix B: Out of steady state analysis

Let the variables Γ, Ω, M and h be defined by:

$$\begin{aligned} \Gamma(t) &= \sum_{i=0}^{\infty} i g^T(i,t) \\ \Omega(t) &= \sum_{i=0}^{\infty} v(i) g^D(i,t) \\ M(t) &= \sum_{i=0}^{\infty} \lambda^{-v(i)} g^T(i,t) \\ h(t) &= g^T(0,t) \end{aligned} \tag{24}$$

where $g^T(i,t)$ and $g^D(i,t)$ are the distribution functions of the technology gap and the domestic gap at time t, respectively. $\Gamma(t)$ and $\Omega(t)$ are the out of steady state counterparts of γ and $\eta(\gamma)$, respectively. Similarly, $1-\lambda M(t)$ is the out of steady state counterpart of $m(\gamma)$. (From here onwards I will suppress the index for time unless necessary to avoid confusion.)

Let V^i denote the value of a firm that has adopted technology for an equipment good which had technology gap i at the time of the adoption (so that it has domestic gap i thereafter), and let $V = \sum_{i=0}^{\infty} V^i g^T(i,t)$. Letting

π^i denote the profits made by a firm importing an equipment good with domestic gap i, the no-arbitrage condition requires

$$\dot{V}^i = (r+\xi)V^i - \pi^i$$

But $\pi^i = P_Z Z(1-\lambda^{1-v(i)})$, and using the out of steady state counterpart of equation 16 this implies that $\pi^i = B\lambda^{-\theta(\Gamma+\Omega-I_N)}(1-\lambda^{1-v(i)})$, where $B \equiv \phi L(\tau R)^{-\theta}$. From the law of motion for $g^T(i,t)$ and $g^D(i,t)$ given in the text, we can get:

$$\dot{V} = (r-\iota)V - B\lambda^{-\theta(\Gamma+\Omega-I_N)}(1-\lambda M) + \iota W \tag{25}$$

where $W = \sum_{i=1}^{\infty} V^i g^T(i-1,t)$. Given the fact that i affects profits only through $(1-\lambda^{1-v(i)})$, then for any equilibrium it must be the case that at any point in time $V^i = \omega(1-\lambda^{1-v(i)})$ for all i, for some term ω which is independent of i. This implies that $V = \omega(1-\lambda M)$, which in turn implies that $\omega = V/(1-\lambda M)$. We thus have that

$$V^i = \frac{V}{1-\lambda M}(1-\lambda^{1-v(i)})$$

In turn, this implies that

$$W = \frac{V}{\lambda}\left(1 + \frac{(\lambda-1)(1-h)}{1-\lambda M}\right)$$

Plugging this into 25 we arrive at the following law of motion for V:

$$\dot{V} = (r-\iota)V - B\lambda^{-\theta(\Gamma+\Omega-I_N)}(1-\lambda M) + \frac{\iota V}{\lambda}\left(1 + \frac{(\lambda-1)(1-h)}{1-\lambda M}\right) \tag{26}$$

Given a path for ξ, differentiation of the variables Γ, Ω, M and h in 24 with respect to time yields the following equations for the law of motion for our state variables:

$$\begin{aligned} \dot{\Gamma} &= \iota - \xi\Gamma \\ \dot{\Omega} &= \xi(\Gamma + h - \Omega) \\ \dot{M} &= \xi/\lambda - (c+\xi)M + (c/\lambda)h \\ \dot{h} &= \xi(1-h) - \iota h \end{aligned} \tag{27}$$

where $c \equiv \iota(1-1/\lambda)$.

An equilibrium is a path for the variables Γ, Ω, M, h, V, and $\xi \geq 0$ such that 26 and 27 are satisfied with the additional restriction that $V = a_A \sigma \lambda^{\theta I_N}$ (where $\sigma \equiv (\phi/\theta)(\lambda R)^{-\theta}$) if $\xi > 0$ and $\xi = 0$ if $V < a_A \sigma \lambda^{\theta I_N}$ and also with the restriction that V is bounded. Equation 26 together with the condition $V = a_A \sigma \lambda^{\theta I_N}$ implies that if $\xi > 0$ then the following condition must be satisfied:

$$\rho - c - b\lambda^{-\theta(\Gamma+\Omega)}(1 - \lambda M) + c\left(\frac{(1-h)}{1-\lambda M}\right) = 0 \tag{28}$$

where $b \equiv B/\sigma a_A$. Using this equation and 27 it is possible to obtain a dynamic system with three state variables, Γ, Ω, and M. This dynamic system determines how these state variables (and consequently also h through 28) evolve along an equilibrium with $\xi > 0$. The stationary points of this dynamic system are determined as in Section 2. In particular, noting that if ξ is constant then Γ, Ω, M, h converge to $\gamma = \iota/\xi$, $\eta(\gamma)$, $\frac{1-m}{\lambda}$, and $\frac{1}{1+\gamma}$, respectively, the value of Γ at a stationary point is given by the solution of the following equation:

$$\frac{m(\gamma)}{(\rho + \iota/\gamma)} = \frac{\lambda^{\theta(\gamma+\eta(\gamma))}}{b} \tag{29}$$

Note that this equation is equivalent to the equation determining the equilibrium level of γ in Section 2 (i.e., equation 19).

I have performed a series of numerical exercises to show that the steady-state equilibrium with the lower level of γ (a stationary point that I henceforth refer to as the low stationary point) is locally stable while the one with the higher level of γ (the high stationary point) is locally unstable. The parameters I use here are the same as in the calibration of Section 4 with the intermediate value for λ: $r = .04$, $\delta = .06$, $\rho = .025$, $\theta = 0.52$, $\lambda = 1.4$, $\iota = 0.086$. The only parameter for which I do not have a numerical value is b. This parameter captures the size of the economy (L), the cost of technology adoption (a_A), and the tariff level (τ); a larger L, a lower a_A, and a lower τ lead to a higher b. For different levels of the parameter b there will be a different set of stationary points. In particular, for $b < 0.4503$ there are no stationary points, whereas for $b = 0.4503$ there is one stationary point and for $b > 0.4503$ there are two stationary points (see Figure A1).

To consider stability, I take different levels of b above 0.4503 and linearize the dynamic system around one of the stationary points determined for that level of b. Doing this for b varying between 0.46 and 30 with a step of .01, one finds that the eigenvalues for the linearized system around the low stationary point are always real and negative, implying stability. For the high stationary point the eigenvalues are initially (for a low level of b) all real, with at least one positive eigenvalue, implying that the stationary point is unstable. At a higher level of b (0.79), two eigenvalues become complex numbers with positive real parts, implying oscillatory instability (i.e., the system spirals outwards in the neighborhood of the stationary point). For an even higher level of b (1.61) all the eigenvalues have negative real roots, implying local stability.

This appears to imply that the stationary points for the low level of γ are always stable, whereas the stationary points for the high level of γ are stable when b is high enough. This is not the case, however, because recall that the dynamic system underlying the previous analysis corresponds to the equilibrium path when the initial conditions are such that equation 28 is satisfied. Consider what happens if the system is initially in steady state and then the parameter b changes. The values of Γ, Ω, M, and h will not satisfy the equation 28 for the new level of b, so either ξ becomes zero (if b decreases) or there is a discrete jump in technology adoption (in the sense that the measure of resources spent in technology adoption is strictly positive at that instant) so that the state variables can jump (if b increases). I now consider each of these cases.

(i) Decrease in b. Starting from a stationary point, a decrease in b at time $t = 0$ will cause technology adoption to fall to zero until the state variables are such that equation 28 is satisfied given the new level of b. To proceed, we need some additional notation. Let $\boldsymbol{\omega} \equiv (\Gamma, \Omega, M, h)$, and let $\boldsymbol{\omega}_{ss}^k(b)$ be the value of $\boldsymbol{\omega}$ at the k=h (for high) or k=l (for low) steady state given b. Finally, let $\tilde{\boldsymbol{\omega}}^k(t;b)$ be the value of $\boldsymbol{\omega}$ at time t given that $\boldsymbol{\omega}$ at time $t = 0$ is $\boldsymbol{\omega}_{ss}^k(b)$, given that $\xi(s) = 0$ for $s \in [0, t]$ and given the dynamic system 27. Since 28 cannot be satisfied at $t = 0$, the equilibrium after the decline in b is either $\xi(t) = 0$ for all $t > 0$, or the equilibrium is given by 27 with $\xi(s) = 0$ and $V(s) < a_A\sigma\lambda^{\theta I_N(s)}$ for $s \in [0, \tilde{t}]$, with $V(\tilde{t}) = a_A\sigma\lambda^{\theta I_N(\tilde{t})}$ and 28 is satisfied for $\tilde{\Gamma}^k(\tilde{t};b)$, $\tilde{\Omega}^k(\tilde{t};b)$, $\tilde{M}^k(\tilde{t};b)$ and $\tilde{h}^k(\tilde{t};b)$; after time $\tilde{t}$ the system evolves according to 27 and 28. To determine $\tilde{t}$ let $y \equiv a_A\sigma\lambda^{\theta I_N}/V$. We can get from 26 that (I suppress the index k unless needed to avoid confusion):

$$\dot{y}(t)/y(t) \equiv c - \rho + b'\lambda^{-\theta(\tilde{\Gamma}(t;b)+\tilde{\Omega}(t;b))}\left(1 - \lambda\tilde{M}(t;b)\right)y(t) - c\left(\frac{1-\tilde{h}(t;b)}{1-\lambda\tilde{M}(t;b)}\right) \tag{30}$$

To understand the implications of this equation, let

$$g_k(t) \equiv c - \rho + b'\lambda^{-\theta(\tilde{\Gamma}^k(t;b)+\tilde{\Omega}^k(t;b))}\left(1 - \lambda\tilde{M}^k(t;b)\right) - c\left(\frac{1-\tilde{h}^k(t;b)}{1-\lambda\tilde{M}^k(t;b)}\right)$$

and let $\tilde{t}^k(b,b') \equiv \min\{t \mid g_k(t) = 0 \text{ and } t > 0\}$. We know that $g_k(0) = (b'-b)m(\gamma)\lambda^{-\theta(\gamma+\eta(\gamma))} < 0$, so the curve $g_k(t)$ must be negative for $t \in [0,\tilde{t}^k]$, intersecting the zero line from below. This implies that if $y(\tilde{t}^k) = 1$, then $y(t) > 1$ for $t \in [0,\tilde{t}^k[$,[27] implying that $\xi = 0$ for $t \in [0,\tilde{t}^k[$ is consistent with the equilibrium restrictions. Now, it can be shown that $g_k'(0) > 0$ if and only if condition

$$\gamma < \frac{1}{\theta \ln(\lambda)} \tag{*}$$

is satisfied. Therefore, if condition (*) is satisfied, then $\tilde{t}^k(b,b')$ is left continuous in b' at $b' = b$, meaning that a small decrease in b leads to a small period in which technology adoption falls to zero. The point $\tilde{\omega}^k(\tilde{t}^k;b)$ is then close to $\omega_{ss}^k(b')$ when b' is close to b (formally, for any $\varepsilon > 0$ $\exists\delta > 0$ s.t. if $b - b' < \delta$ then $||\tilde{\omega}^k(\tilde{t}^k;b) - \omega_{ss}^k(b')||$) which implies that — if the system is locally stable around the stationary point $\omega_{ss}^k(b')$— the system will converge to $\omega_{ss}^k(b')$.

Now consider what happens when condition (*) is not satisfied. In this case $g'(0) \leq 0$, so $t'(b,b')$ becomes left discontinuous at $b' = b$; that is, a small decrease in b leads to a long period of no technology adoption (i.e., high $\tilde{t}^k$), so the point $\tilde{\omega}^k(t';b)$ in this case is far away from the stationary point associated with b'. Local stability then does not imply that the system will converge to $\omega_{ss}^k(b')$.

It turns out that — for the numerical values of the parameters given above— all the low stationary points for $b > 0.4503$ satisfy condition (*),

[27] To see this, note first that the function $y'(t)$ is the same as the function $g(t)$ around $t = \tilde{t}^k$ (i.e., $y^n(\tilde{t}^k) = g^{n-1}(\tilde{t}^k)$ for all $n \geq 1$). The fact that $g(t) < 0$ for $t \in [0,\tilde{t}^k[$ then implies that $y(\tilde{t}^k - \varepsilon) > 1$. Now, if $y(t) < 1$ for some $t \in [0,\tilde{t}^k[$, then $y(t)$ must cross the line $y = 1$ from below at some $t < \tilde{t}^k$, say at t_o. But then $\dot{y}(t_o) = g(t_o) < 0$, a contradiction.

whereas all the high stationary points that are locally stable do not satisfy condition (*). We can thus be confident that, starting at the low stationary point with the low level of γ, a small decrease in b leads to an equilibrium path that converges to the low stationary point for the new level of b; we cannot say the same thing when the system starts at the high stationary point, even when it is locally stable (i.e., for $b \geq 1.61$). Not being sure that the system converges back to the high stationary point does not mean that it does not, however, so I have examined the issue numerically. For $b \geq 1.61$ $g_h(t) < 0$ for all t if $b' < b$, implying that the only equilibrium after the negative shock entails $\xi = 0$ forever.

(ii) Increase in b. Starting from a stationary point, an increase in b to b' will cause a discrete increase in technology adoption so that —given the induced jump in the state variables— equation 28 is satisfied for b'. It is readily shown that if condition (*) is satisfied at the stationary point then a small discrete increase in technology adoption will restore equation 28 when $b' - b$ is small. To be more precise, let $\Delta^k(b, b')$ denote the discrete increase in technology adoption caused by the increase in b from b to b', and let $\hat{\omega}^k(\Delta, b)$ be the value of ω after a discrete increase in technology adoption of Δ when the system was originally at rest with $\omega = \omega^k_{ss}(b)$. It can be shown that if condition (*) is satisfied for $\tilde{\omega}^k(\Delta)$ then $\Delta^k(b, b')$ is right continuous in b' at $b' = b$. For $b' - b$ small then $\hat{\omega}^k(\Delta, b)$ is close to $\omega^k_{ss}(b')$, implying that a small increase in b to b' eventually takes the system to the steady state $\omega^k_{ss}(b')$.

Things are different when condition (*) is not satisfied at the stationary point. In this case there must be a large discrete increase in technology adoption to restore equation 28 after an increase in b. Formally, $\Delta(b, b')$ is not right continuous in b' at $b' = b$. For instance, $\lim_{b' \to 2^+} \Delta^h(2, b') = 0.76$. This will take the system far away from the new stationary point $\omega^h_{ss}(b')$, so the system may not converge to that stationary point.

Since all the low stationary points for $b > 0.4503$ satisfy condition (*), the local stability of the system at the low stationary point implies that a small increase in b to b' leads the system eventually to the steady state $\omega^l_{ss}(b')$.

I now examine whether the low steady-state equilibrium is isolated, in the sense that if $\omega(t) = \omega^l_{ss}(b)$ for $t = 0$, then the unique equilibrium entails $\omega(t) = \omega^l_{ss}(b)$ for all $t \geq 0$. I will show that this is the case if a condition that is slightly stronger than condition (*) is satisfied, namely,

$$\gamma + \frac{1}{1+\gamma} < \frac{1}{\theta \ln(\lambda)}. \tag{+}$$

First, note that there are only two possible alternative equilibria: one in which $\xi(t) = 0$ for all $t \geq 0$ and another in which $\xi(t) = 0$ for $t \in [0, \varepsilon]$ and $\xi(t) > 0$ for some $t > \varepsilon$.

I first show that $\xi(t) = 0$ for all $t \geq 0$ is not an equilibrium. If $\xi(t) = 0$ for all $t \geq 0$, then at time $t = 0$ the value of a firm that has succeeded in technology adoption but does not yet know for which input is $\tilde{V}_0 = \frac{\sum \pi_0^i g^T(i,0)}{r}$, whereas in the equilibrium with $\xi(t) = \hat{\xi}$ for all $t \geq 0$ the corresponding value is $V_0 = \frac{\sum \pi_0^i g^T(i,0)}{r + \hat{\xi} - \theta\iota \ln(\lambda)}$. Condition (*) implies that $r + \hat{\xi} - \theta\iota \ln(\lambda) > r$, which implies that $\tilde{V}_0 > V_0 = a_A \sigma \lambda^{\theta I_N(0)}$. But then $\xi(0)$ cannot be zero in equilibrium.

I now show that there is no equilibrium with $\xi(t) = 0$ for $t \in [0, \varepsilon]$ and $\xi(t) > 0$ for some $t > \varepsilon$. It can be shown that if condition (*) is satisfied, then $g(t)$ is first rising from zero and then falling, with $\lim_{t \to \infty} g(t) = -\rho$. This implies that there is a unique value for $t > 0$ at which $g(t) = 0$; let t_0 denote this level of t. Note for future reference that $g'(t_0) < 0$. Let $\tilde{t} \equiv Inf\{t > 0 | \xi(t) > 0\}$. The fact that $V(t)$ along any equilibrium must be continuous implies that $V(\tilde{t}) = a_A \sigma \lambda^{\theta I_N(\tilde{t})}$, implying that $y(\tilde{t}) = 1$.

I now show that $\tilde{t} = t_0$. To show this, assume by contradiction that $\tilde{t} < t_0$; then $g(\tilde{t}) > 0$, which together with $y(\tilde{t}) = 1$ and equation 30 implies that $\dot{y}(\tilde{t}) > 0$, which implies that $y(\tilde{t} - \vartheta) < 1$ or $V(\tilde{t} - \vartheta) > a_A \sigma \lambda^{\theta I_N(\tilde{t} - \vartheta)}$ for any small ϑ, contradicting the assumption that $\xi(t) = 0$ for $t < \tilde{t}$. Now assume that $\tilde{t} > t_0$. Then $g(\tilde{t}) < 0$, which implies that $\dot{y}(\tilde{t}) < 0$. Consequently, $y(\tilde{t} + \vartheta) < 1$ or $V(\tilde{t} + \vartheta) > a_A \sigma \lambda^{\theta I_N(\tilde{t} - \vartheta)}$ for any small ϑ. This could be an equilibrium if at time $\tilde{t}$ there was a discrete level of technology adoption such that the state variables jump in such a way that g becomes zero at $\tilde{t}$. But it can be shown that condition (+) implies that such a jump is not possible, since any discrete level of technology adoption induces a jump in the state variables such that g actually decreases.[28]

[28]Let x_* represent the value of variable x just before the discrete increase in technology adoption, and let x_+ be the corresponding value after the event. A discrete technology adoption of Δ implies that $\Gamma_+ + \Omega_+ = \Gamma_* + \Omega_- + \Delta(h_* - \Omega_*)$, $M_+ = \Delta/\lambda + (1 - \Delta)M_*$ and $h_+ = h_* + \Delta(1 - h_*)$. Therefore, $g_+ - g_* = b\lambda^{-\theta(\Gamma_* + \Omega_*)}(1 -$

Since $\tilde{t} = t_0$, then we have that $y(\tilde{t}) = 1$ and $\dot{y}(\tilde{t}) = 0$. But since $g'(\tilde{t}) < 0$, then it can be shown that $y(\tilde{t} - \vartheta) < 1$ for any small ϑ, so the assumption that $\xi(t) = 0$ for $t < \tilde{t}$ is inconsistent with the equilibrium restrictions.

8 Appendix C: Proof of Proposition 1

To derive equation 22 it is first necessary derive an expression for net income J. Since in equilibrium we have $\alpha A Z^{\alpha} K^{\beta} H^{\varsigma} L^{\varphi} = P_Z Z$, then output in South satisfies $y = (\phi/\alpha) L P_Z^{-\theta}$. Now consider the cost of renting equipment goods from North. This is given by:

$$\lambda R \int_0^1 x(j) dj$$

where $x(j)$ is the quantity of equipment good j used in South and therefore rented from Northern firms. Since expenditure is the same for all equipment goods, then $x(j) = \frac{P_Z Z}{\tau R \lambda^{v(i(j))}}$, where $i(j)$ represents the domestic gap of equipment good j. The cost of renting equipment goods from North is therefore

$$\lambda R P_Z Z \int_0^1 \frac{\lambda^{-v(i(j))}}{\tau R} dj = (\lambda/\tau) P_Z Z \Psi$$

where $\Psi \equiv \int_0^1 \lambda^{-v(i(j))} dj = \sum_{i=0}^{\infty} \lambda^{-v(i)} g^D(i,t)$. Since J is equal to y net of the cost of renting equipment from North and the cost of technology adoption, then using the previous equation and $P_Z Z = \phi L P_Z^{-\theta}$ we get:

$$J = (\phi/\alpha) L P_Z^{-\theta} - \phi(\lambda/\tau) L P_Z^{-\theta} \Psi - a_A \sigma \lambda^{\theta I_N} \xi$$

Using $P_Z = \tau R \lambda^{\Gamma+\Omega-I_N}$ we finally get:

$$J = \lambda^{\theta I_N} \left(\phi L (\tau R)^{-\theta} (1/\alpha - (\lambda/\tau)\Psi) \lambda^{-\theta(\Gamma+\Omega)} - a_A \sigma \xi \right)$$

I now use this expression for J to derive an expression for Q. Using $Q = J/w$ and $w = P_Z Z/\theta L = (\phi/\theta)(\tau R)^{-\theta} \lambda^{-\theta(\Gamma+\Omega-I_N)}$ (the second equality comes from equation 16) we get

$$Q = \theta L (1/\alpha - (\lambda/\tau)\Psi) - a_A \xi (\tau/\lambda)^{\theta} \lambda^{\theta(\Gamma+\Omega)}$$

$\lambda M_*) \left(\lambda^{-\theta\Delta(h_* - \Omega_*)}(1-\Delta) - 1 \right)$. Some algebra shows that condition (**) implies that $g_+ - g_* < 0$ for all Δ, implying that no discrete increase in technology adoption can make g equal to zero.

Using $\Psi^{ss} = \frac{1-m(\gamma)}{\lambda}$, $\Gamma^{ss} = \gamma$ and $\Omega^{ss} = \eta(\gamma)$ this implies that $Q^{ss} = \theta L(1/\alpha - (1-m)/\tau) - a_A\xi(\tau/\lambda)^\theta\lambda^{\theta(\gamma+\eta)}$. One can also get:

$$\frac{dQ(t)}{d\Delta}|_{\Delta=0} = \frac{d\Pi(t)}{d\Delta}|_{\Delta=0} - a_A\hat{\xi}(\tau/\lambda)^\theta\lambda^{\theta(\hat{\gamma}+\hat{\eta})}\ln(\lambda)\theta\frac{d(\Gamma(t)+\Omega(t))}{d\Delta}|_{\Delta=0}$$

Using $w = (\phi/\theta)(\tau R)^{-\theta}\lambda^{-\theta(\Gamma+\Omega-I_N)}$ and these expressions for Q^{ss} and $\frac{dQ(t)}{d\Delta}|_{\Delta=0}$ one can get:

$$\begin{aligned} & \int_0^\infty e^{-rt}w^{ss}(t)\frac{dQ(t)}{d\Delta}|_{\Delta=0}dt \\ +\int_0^\infty e^{-rt}Q^{ss}\frac{dw(t)}{d\Delta}|_{\Delta=0}dt = {} & \lambda^{\theta I_N(0)}N\Big[-E\int_0^\infty e^{-\rho t}\frac{d\Gamma(t)}{d\Delta}|_{\Delta=0}dt - E\int_0^\infty e^{-\rho t}\frac{d\Omega(t)}{d\Delta}|_{\Delta=0}dt \\ & +(1/\theta L)\int_0^\infty e^{-\rho t}\frac{d\Pi(t)}{d\Delta}|_{\Delta=0}dt\Big] \end{aligned}$$

where $N \equiv \phi L(\tau R)^{-\theta}\lambda^{-\theta(\hat{\gamma}+\hat{\eta})}$ and $E \equiv \theta\ln(\lambda)(1/\alpha - (1-\hat{m})/\tau)$. Using the equilibrium condition for γ this immediately leads to equation 22.

I now determine each of the first three terms in the parenthesis of the RHS of equation 22. Using the equations for the law of motion of Γ and Ω derived in Appendix B, we can get

$$\Gamma(t) = \gamma - \Delta\gamma e^{-\xi t}$$

and

$$\Omega(t) = \eta - \Delta(\frac{1}{1+\gamma})e^{-\xi t}(e^{-\iota t} - 1) - \Delta\iota e^{-\xi t}t$$

(to simplify notation I now suppress the hat to indicate that a variable is in steady state). From these expressions it can be shown that:

$$\int_0^\infty e^{-\rho t}\frac{d\Gamma(t)}{d\Delta}|_{\Delta=0}dt = -\frac{\gamma}{\rho+\xi} \tag{31}$$

and

$$\int_0^\infty e^{-\rho t}\frac{d\Omega(t)}{d\Delta}|_{\Delta=0}dt = -\left(\frac{1}{\rho+\xi}\right)\left(\frac{\iota}{\rho+\xi} - \frac{\iota}{(1+\gamma)(\rho+\iota+\xi)}\right) \tag{32}$$

From the equations $Q = L + \Pi - a_A\sigma\lambda^{\theta I_N}\xi/w$ and $Q = J/w$ I get $\Pi = J/w - L + a_A\sigma\lambda^{\theta I_N}\xi/w$. Using $w = (\phi/\theta)(\tau R)^{-\theta}\lambda^{-\theta(\Gamma+\Omega-I_N)}$ this implies that

$$\Pi = \theta L\left(1/\alpha - (\lambda/\tau)\Psi\right) - L$$

which in turn implies that

$$\int_0^\infty e^{-\rho t}\frac{d\Pi(t)}{d\Delta}|_{\Delta=0}dt = -\theta L(\lambda/\tau)\int_0^\infty e^{-\rho t}\frac{d\Psi(t)}{d\Delta}|_{\Delta=0}dt \tag{33}$$

From 20 one can show that the law of motion for Ψ is

$$\dot{\Psi}(t) = \xi(M - \Psi)$$

which implies that

$$\Psi(t) = (1-m)e^{-\xi t} + \xi\int M(s)e^{-(t-s)\xi}ds$$

and hence

$$\frac{d\Psi(t)}{d\Delta}|_{\Delta=0} = \xi\int\frac{dM(s)}{d\Delta}|_{\Delta=0}e^{-(t-s)\xi}ds \tag{34}$$

From the law of motion for M derived in Appendix B one can get:

$$M(t) = \left(\frac{1-m}{\lambda} + \Delta\frac{m}{\lambda}\right)e^{-(c+\xi)t} + \int_0^t (c/\lambda)h(s) + \xi/\lambda)e^{-(t-s)(c+\xi)}ds$$

which implies

$$\begin{aligned}\frac{dM(t)}{d\Delta}|_{\Delta=0} &= (m/\lambda)e^{-(c+\xi)t} + \int_0^t (c/\lambda)\frac{dh(s)}{d\Delta}|_{\Delta=0}e^{-(t-s)(c+\xi)}ds \\ &= (m/\lambda)e^{-(c+\xi)t} - \left(\frac{c}{\iota+\xi}\right)\left(e^{-(\iota+\xi)t} - e^{-(\iota+\xi-\iota/\lambda)t}\right)\end{aligned}$$

Plugging this into 34 yields, after some manipulation,

$$\frac{d\Psi(t)}{d\Delta}|_{\Delta=0} = \left(\frac{1}{1+\gamma} + \frac{m}{\gamma(\lambda-1)}\right)\left(e^{-\xi t} - e^{-(c+\xi)t}\right) + \left(\frac{\lambda-1}{\lambda(1+\gamma)}\right)\left(e^{-(\iota+\xi)t} - e^{-\xi t}\right)$$

Finally, plugging this into 33 and integrating yields, again after some manipulation,

$$\begin{aligned}&\int_0^\infty e^{-\rho t}\frac{d\Pi(t)}{d\Delta}|_{\Delta=0}dt \qquad (35)\\ =\;& \left(\frac{\theta L}{\rho+\xi}\right)\left(\frac{\lambda-1}{1+\gamma}\right)\frac{\iota}{\tau}\left[\left(\frac{1}{\rho+\iota+\xi}\right) - \left(\frac{\lambda(1+\gamma)}{(\lambda+\gamma(\lambda-1))}\right)\left(\frac{1}{\rho+\xi+c}\right)\right]\end{aligned}$$

Plugging 31, 32 and 35 into 22 finally yields

$$\Upsilon'(0) - a_A\sigma\lambda^{\theta I_N(0)} = \lambda^{\theta I_N(0)}\left(\frac{N}{\rho+\xi}\right)\left[E\gamma + E\left(\frac{\iota}{\rho+\xi} - \frac{\iota}{(1+\gamma)(\rho+\iota+\xi)}\right)\right.$$
$$\left. + \left(\frac{\lambda-1}{1+\gamma}\right)\frac{\iota}{\tau}\left[\left(\frac{1}{\rho+\iota+\xi}\right) - \left(\frac{\lambda(1+\gamma)}{(\lambda+\gamma(\lambda-1))}\right)\left(\frac{1}{\rho+\xi+c}\right)\right] - m(\gamma)\right]$$

In an appendix vailable upon request I have shown that this expression is *always* positive.

9 Appendix D: Proof of Proposition 3

The following lemma (whose proof is available from the author upon request) is used to prove Proposition 2:

Lemma 3 *Let* $\Lambda(\Delta) \equiv \int_0^\infty e^{-\rho t}[f(\mathbf{x}_t) + a\zeta_t]dt$ *where* $\mathbf{x}_t \in \Re^n$ *with* $\dot{\mathbf{x}}_t = (\mathbf{c}_1\zeta_t + \mathbf{c}_2)\mathbf{x}_t$ *, where* $\mathbf{c}_1$ *and* $\mathbf{c}_2$ *are nxn constant matrixes,* $\mathbf{x}_t = \hat{\mathbf{x}}$ *for* $t < 0$ *and* $\zeta_t = \hat{\zeta} + \Delta\delta(t)$*, where* $(\mathbf{c}_1\hat{\zeta}_t + \mathbf{c}_2)\hat{\mathbf{x}}_t = 0$*, where* $\delta(t)$ *is Dirac's delta and* f *is continuous. Let* $\tilde{\Lambda}(z) \equiv \int_0^\infty e^{-\rho t}[f(\tilde{\mathbf{x}}_t) + a\tilde{\zeta}_t]dt$ *with* $d\tilde{\mathbf{x}}_t/dt = (\mathbf{c}_1\tilde{\zeta}_t + \mathbf{c}_2)\tilde{\mathbf{x}}_t$*,* $\tilde{\mathbf{x}}_t = \hat{\mathbf{x}}$ *for* $t < 0$ *and* $\tilde{\zeta}_t = \hat{\zeta} + zN(t)$*, where* $N(t)$ *is continuous and bounded and satisfies* $\int_0^\infty e^{-\rho t}N(t)dt > 0$*. Then* $\Lambda'(0) > 0$ *implies* $\tilde{\Lambda}'(0) > 0$*.*

To prove proposition 2, I show that the problem can be mapped into the conditions of the previous lemma. Let $\mathbf{x} \equiv (\Gamma, \Omega, \Psi, M, h, 1)$,

let $f(\mathbf{x}) \equiv \phi L(\tau R)^{-\theta}(1/\alpha - (\lambda/\tau)\Psi(t))\,\lambda^{-\theta(\Gamma(t)+\Omega(t))}$, let $a \equiv a_A\sigma$ and let $\zeta_t = \xi_t$. It can be shown that $\dot{\Psi} = \xi(M - \Psi)$, which together with the dynamic system in 27 implies that $\dot{\mathbf{x}} = (c_1\xi + c_2)\mathbf{x}$, where

$$\mathbf{c}_1 \equiv \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1/\lambda \\ 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \text{ and } \mathbf{c}_2 \equiv \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \iota \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -c & c/\lambda & 0 \\ 0 & 0 & 0 & 0 & -\iota & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Proposition 1 implies that $\Lambda'(0) > 0$. To proceed, let us focus on an increase in the tariff, which goes from τ_0 to τ_1 at time $t = 0$. Let $N(t) \equiv \frac{\partial \xi_t}{\partial \tau}|_{\tau=\tau_0}$. For τ_1 close to τ_0, we have that $\xi(t)$ is approximately equal to $\hat{\xi} + (\tau_1 - \tau_0)N(t)$, with the approximation getting exact as $(\tau_1 - \tau_0)$ goes to zero. Letting $z \equiv \tau_1 - \tau_0$, then $\tilde{\Lambda}'(0)$ is the derivative of the present discounted value of net income with respect to the tariff. The above lemma then implies that this derivative is positive as long as $\int_0^\infty e^{-\rho t} \left(\frac{\partial \xi_t}{\partial \tau} |_{\tau=\tau_0} \right) dt$ proving Proposition 2. The exact same argument holds for an increase in a_A.

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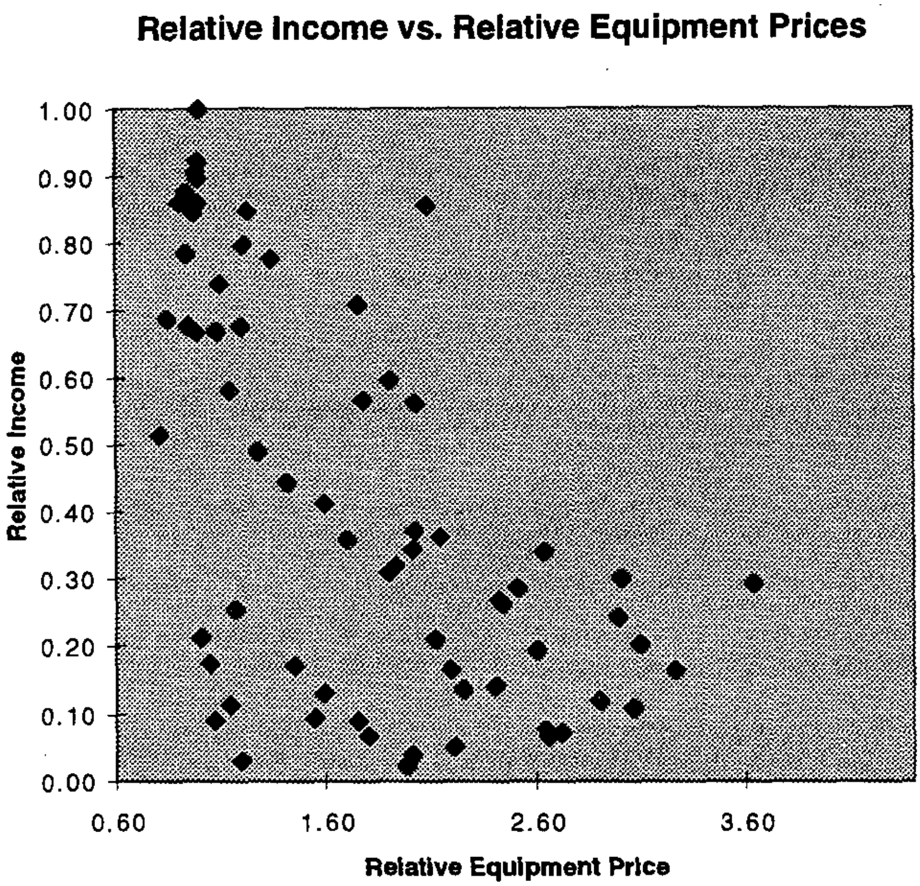
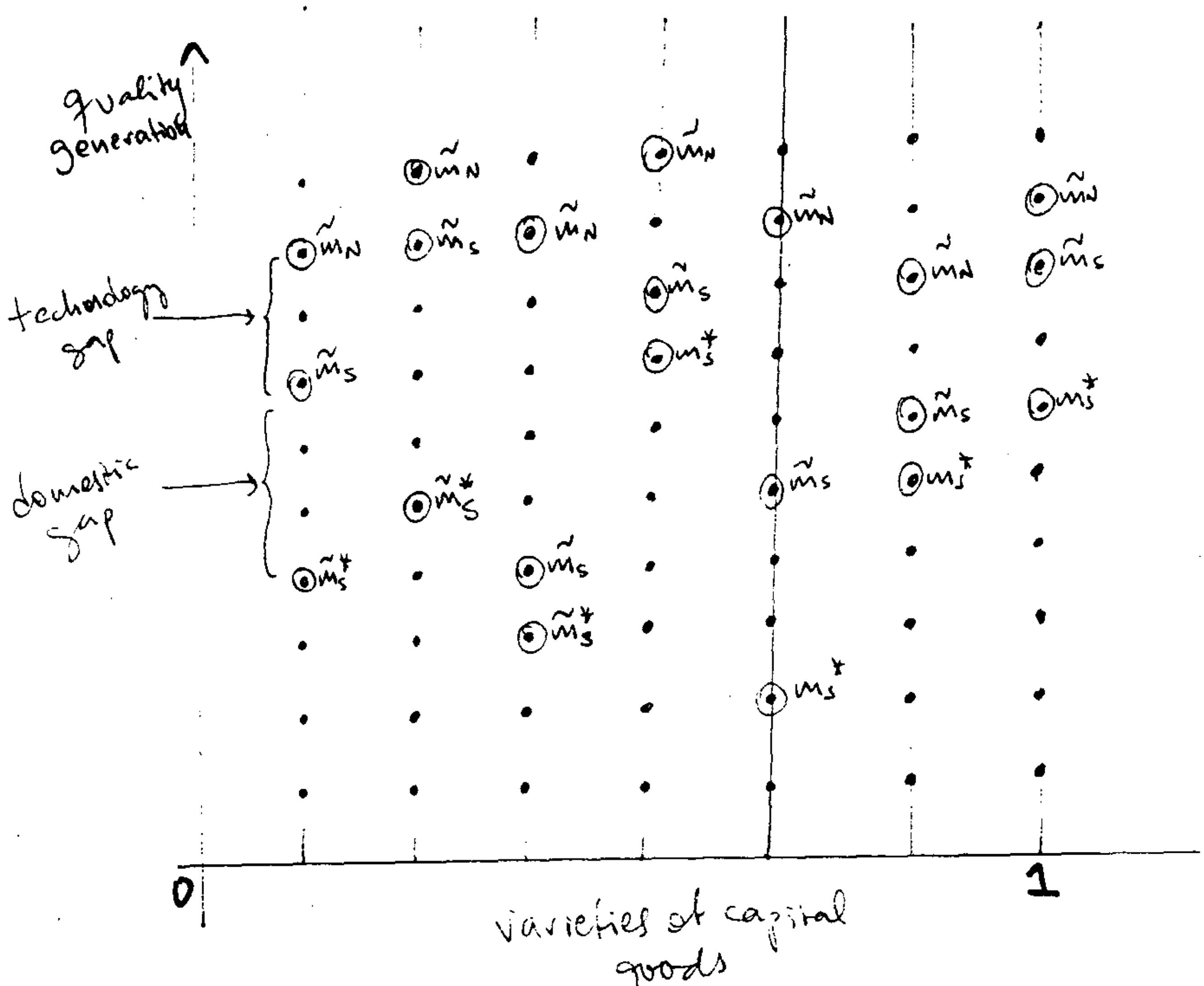
Figure 1



Relative Income vs. Relative Equipment Prices
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Relative Income
0.60
1.60
2.60
3.60
Relative Equipment Price

Figure 2



$\tilde{m}_S^*$ denotes the most advanced generation of a particular capital good in North when it was last adopted in South

Figure 3

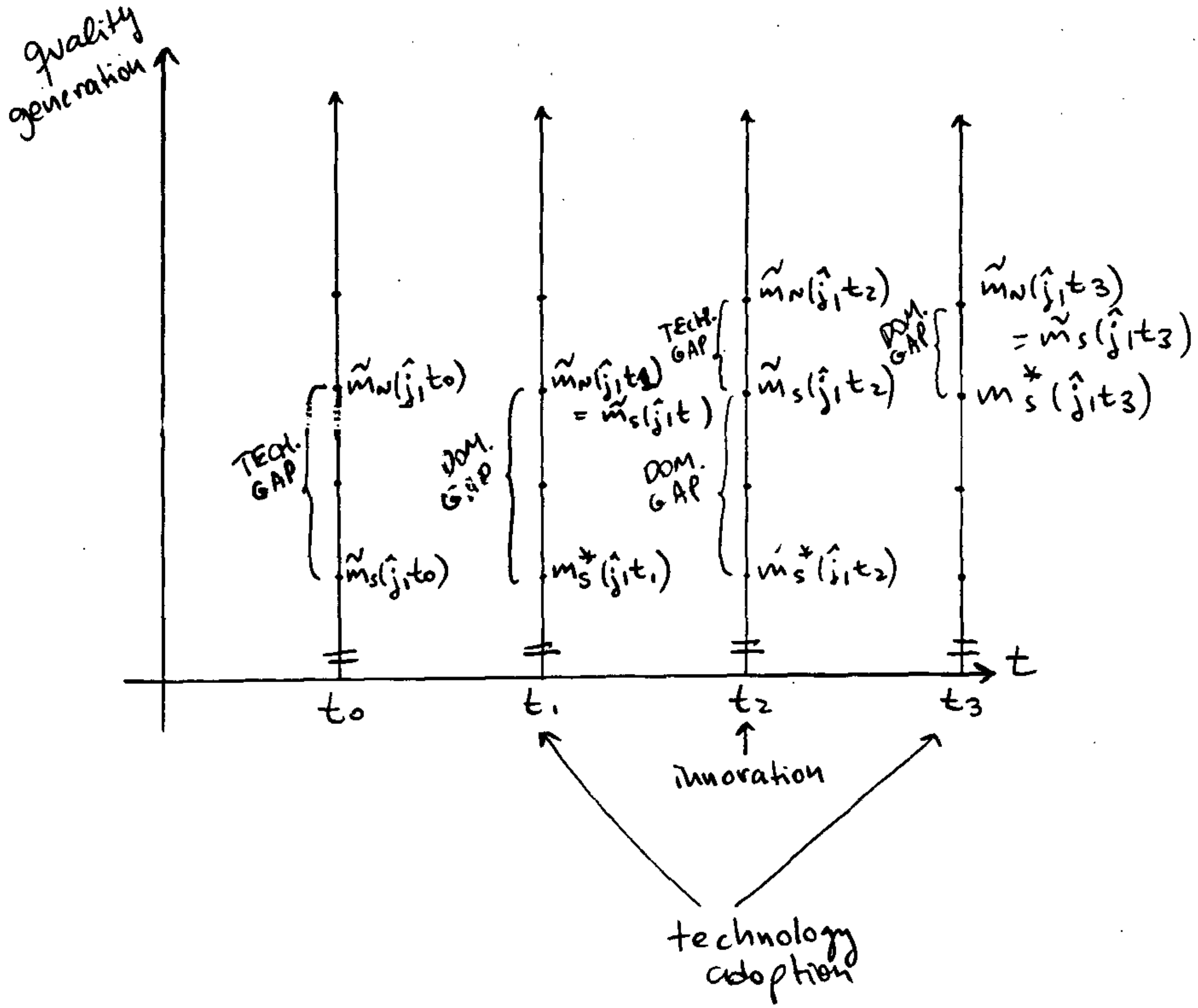

quality generation
TECH. GAP
DOM. GAP
TECH. GAP
DOM. GAP
DOM. GAP
t
t_0
t_1
t_2
t_3
innovation
technology adoption

Figure 4

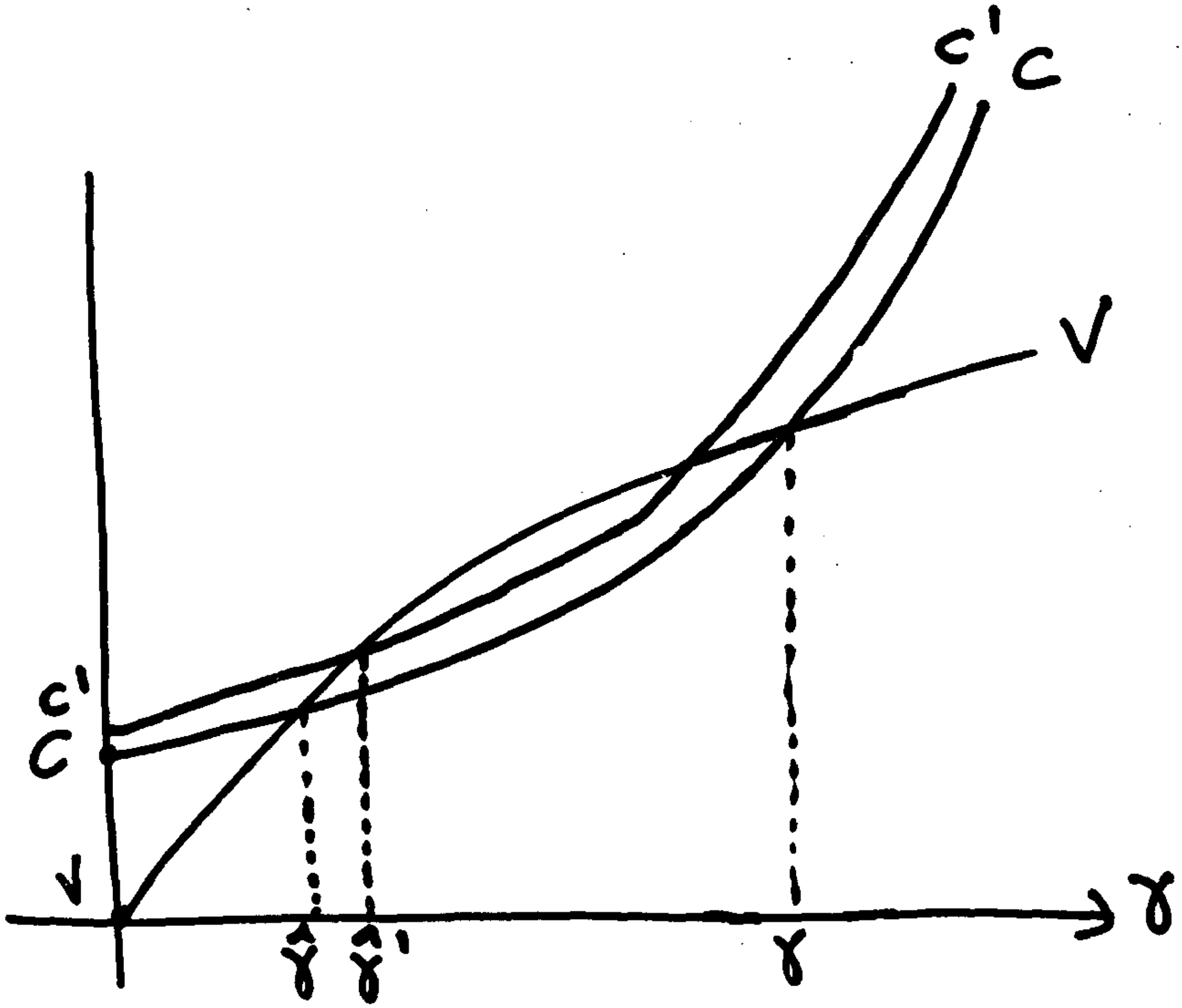
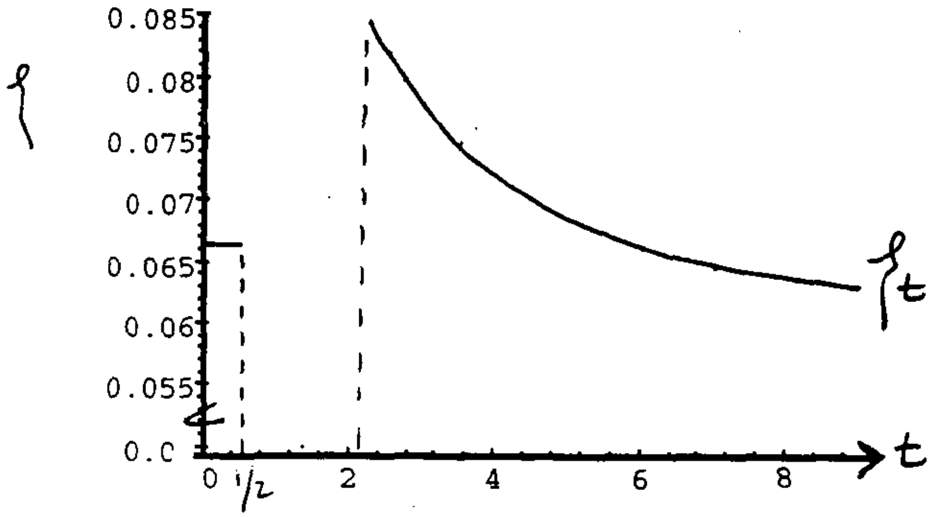


Figure 5



Adjustment path for ξ_t after decrease in $b \equiv \phi(\tau R)^{-\theta} L/a_A \mu$ from 1 to 0.9 at $t = \frac{1}{2}$.

In this case

$$\int_{1/2}^{\infty} e^{-\rho t} \xi_t \, dt \leq 2.64 < 2.89 = \hat{\xi}/\rho$$

Figure 6

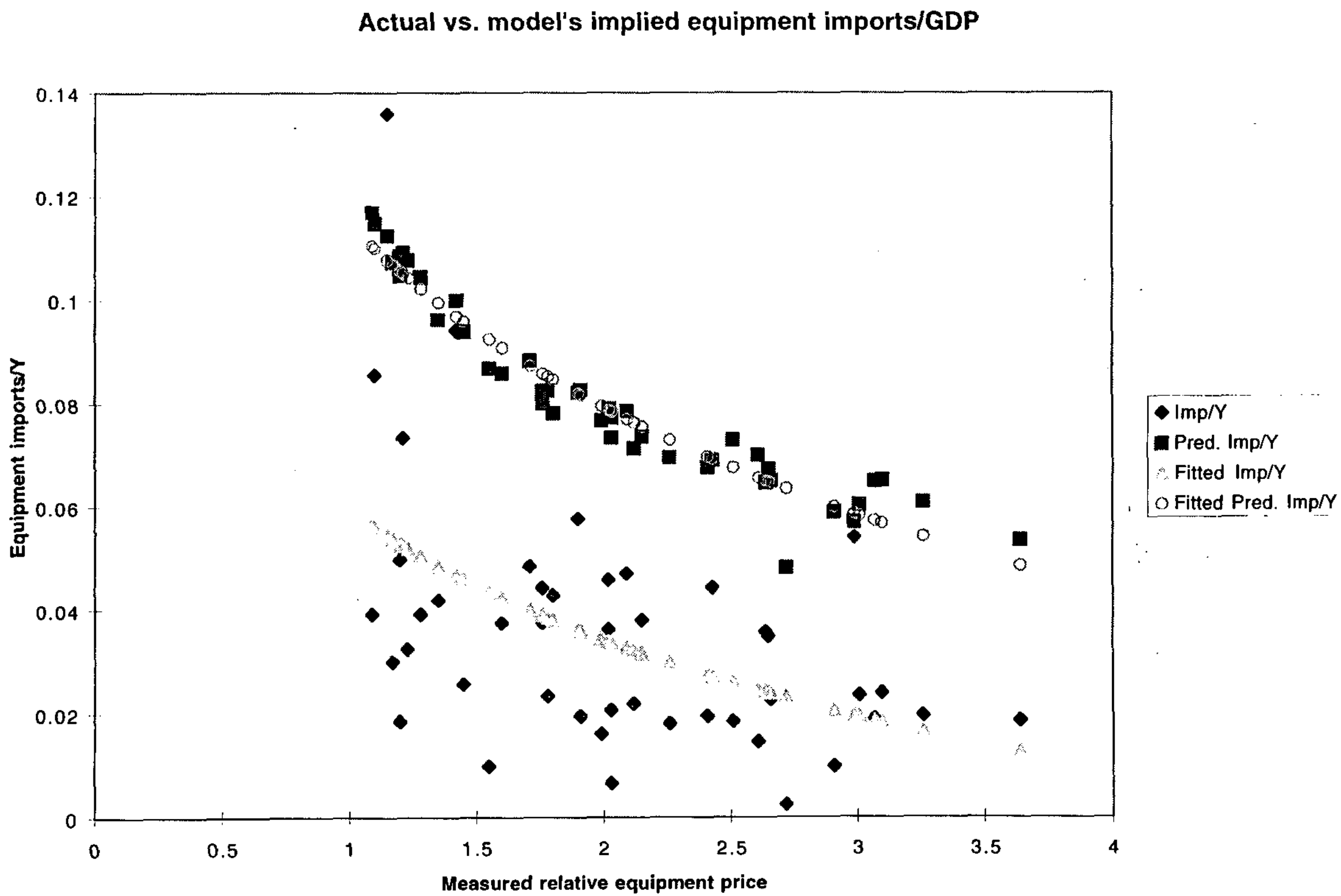

Actual vs. model's implied equipment imports/GDP
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Equipment imports/Y
Measured relative equipment price
Imp/Y
Pred. Imp/Y
Fitted Imp/Y
Fitted Pred. Imp/Y

Table 1
Impact of tariffs and barriers to technology adoption on steady-state relative income given an initial relative income of 0.75 (with τ=1, μ=0)

τ (with μ=0)	μ (with τ=1)	Relative Income	Percentage change relative to τ=1, μ=0
1	0	0.75	0
1.1	0.29	0.71	-5.8
1.2	0.55	0.67	-10.8
1.5	1.13	0.58	-22.7
2	1.66	0.48	-36.2
2.3	1.82	0.43	-42.0

Table 2
Impact of a 10% tariff or a 10% barrier to technology adoption on steady-state relative income for different initial relative income levels

Initial relative income	τ =1.1 (with μ=0)	μ=0.1 (with τ=1)
0.85	-5.3	-0.9
0.75	-5.8	-2.0
0.65	-6.7	-3.9
0.55	-8.5	-8.0
0.45	-14.9	**

** Given the initial relative income, τ=1 and μ=0.1 imply a zero level of technology adoption, and no steady state relative income.

Table 3
Decomposition of the impact of a 10% tariff on steady-state relative income for different initial relative income levels

Initial relative income	Direct effect only	Total effect
0.85	-5.2	-5.3
0.75	-5.2	-5.8
0.65	-5.2	-6.7
0.55	-5.2	-8.5
0.45	-5.2	-14.9

Table 4

Country	yrel	Pmz/Pmz(US)	Tariff	Gamma	Pz/Pz(US)	Pred. yrel	Years behind	Imp/Y*	Pred. Imp/Y
CAMEROON	0.09	1.76	0.26	1.6	3.02	0.56	18.60	0.04	0.08
ETHIOPIA	0.02	1.99	0.2	2.18	4.14	0.48	25.35	0.02	0.08
KENYA	0.07	1.8	0.28	1.65	3.15	0.55	19.19	0.04	0.08
MADAGASCAR	0.07	2.66	0.26	2.98	7.24	0.36	34.65	0.02	0.07
MALAWI	0.04	2.02	0.12	2.45	4.6	0.45	28.49	0.04	0.08
MOROCCO	0.21	2.12	0.3	2.14	4.36	0.46	24.88	0.02	0.07
SENEGAL	0.08	2.65	0.19	3.14	7.62	0.35	36.51	0.03	0.07
TANZANIA	0.03	1.2	0.17	0.32	1.34	0.86	3.72	0.05	0.10
TUNISIA	0.27	2.43	0.22	2.79	6.21	0.39	32.44	0.04	0.07
ZIMBABWE	0.09	1.55	0.23	1.25	2.36	0.64	14.53	0.01	0.09
COSTA-RICA	0.34	2.02	0.16	2.35	4.45	0.46	27.33	0.05	0.08
EL-SALVADOR	0.19	2.61	0.13	3.24	7.75	0.34	37.67	0.01	0.07
GUATEMALA	0.29	2.51	0.08	3.27	7.54	0.35	38.02	0.02	0.07
JAMAICA	0.17	1.45	0.11	1.4	2.33	0.64	16.28	0.03	0.09
MEXICO	0.60	1.91	0.08	2.39	4.27	0.47	27.79	0.02	0.08
ARGENTINA	0.56	2.03	0.29	2	3.98	0.49	23.26	0.02	0.07
BOLIVIA	0.20	3.1	0.13	3.79	11.09	0.29	44.07	0.02	0.07
BRAZIL	0.37	2.03	0.16	2.36	4.49	0.46	27.44	0.01	0.08
CHILE	0.36	2.15	0.21	2.4	4.81	0.44	27.91	0.04	0.07
COLOMBIA	0.30	3.01	0.31	3.24	8.94	0.32	37.67	0.02	0.06
ECUADOR	0.34	2.64	0.28	2.91	7.03	0.36	33.84	0.04	0.06
PARAGUAY	0.24	2.99	0.46	2.87	7.84	0.34	33.37	0.05	0.06
PERU	0.29	3.64	0.41	3.6	12.23	0.27	41.86	0.02	0.05
URUGUAY	0.41	1.6	0.21	1.42	2.57	0.61	16.51	0.04	0.09
VENEZUELA	0.71	1.76	0.18	1.83	3.26	0.54	21.28	0.04	0.08
HONG-KONG	0.44	1.42	0	1.66	2.48	0.62	19.30	0.09	0.10
INDIA	0.07	2.72	1.32	0.97	3.77	0.5	11.28	0.00	0.05
INDONESIA	0.11	3.07	0.14	3.74	10.78	0.29	43.49	0.02	0.06
IRAQ	0.86	2.09	0.09	2.67	5.13	0.43	31.05	0.05	0.08
KOREA,REP.	0.25	1.17	0.14	0.35	1.32	0.87	4.07	0.03	0.11
MALAYSIA	0.31	1.9	0.09	2.37	4.22	0.47	27.56	0.06	0.08
PAKISTAN	0.12	2.91	0.41	2.89	7.68	0.35	33.60	0.01	0.06
PHILIPPINES	0.16	3.26	0.22	3.71	11.37	0.28	43.14	0.02	0.06
SRI-LANKA	0.14	2.41	0.28	2.6	5.78	0.4	30.23	0.02	0.07
SYRIA	0.57	1.78	0.16	1.93	3.41	0.53	22.44	0.02	0.08
THAILAND	0.14	2.26	0.29	2.36	4.99	0.43	27.44	0.02	0.07
AUSTRIA	0.74	1.1	0.05	0.46	1.28	0.88	5.35	0.09	0.11
GREECE	0.49	1.28	0.04	1.15	1.89	0.72	13.37	0.04	0.10
IRELAND	0.58	1.15	0.02	0.8	1.5	0.81	9.30	0.14	0.11
ITALY	0.85	1.23	0.02	1.08	1.78	0.74	12.56	0.03	0.11
NORWAY	0.80	1.21	0.01	1.05	1.73	0.75	12.21	0.07	0.11
PORTUGAL	0.27	1.71	0.05	2.14	3.5	0.52	24.88	0.05	0.09
SPAIN	0.68	1.2	0.04	0.9	1.63	0.78	10.47	0.02	0.11
U.K.	0.67	1.09	0.02	0.54	1.3	0.87	6.28	0.04	0.12
NEW-ZEALAND	0.78	1.35	0.18	0.87	1.8	0.74	10.12	0.04	0.10

*Imp/Y refers to 1980 imports of equipment at current dollars as a ratio of GDP in 1980 international dollars (Summers and H

Table 5

Regression of measured 1980 relative price of equipment (from Jones, 1994) on the tariff (from Lee, 1993), 1980 population and distance (the average distance to the world's 20 major exporters of manufactures, taken from the Barro-Lee data set)*

Variable	Coefficient	s.e. of coefficient	t-ratio
Constant	1.05	0.19	5.62
Tariff	2.64	0.6	4.43
Population	-0.003	0.001	-2.69
Distance	0.07	0.03	2.25

The R^2 of this regression is 42.4%. The F-ratio is 13.2.

* The countries included in the regression are the 58 countries for which I have data for the relative price of equipment in 1980 (i.e., the countries in Jones, 1994) and for the tariff (i.e., the countries in Lee, 1993), excluding the countries which had relative equipment prices higher than in the United States.

Figure A 1