The Role of Education Signaling in Explaining the Growth of College Wage Premium

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Abstract

This paper incorporates an explicit education signaling mechanism into a dynamic model of production and asks if "higher education as a signal" helps explain the simultaneous increase in the supply and price of skilled relative to unskilled labor, as is observed in the US since 1980. The key mechanism is that if college degrees serve as a signal of unobservable talent and talent is productive at the workplace, then improved access to college will enable a higher fraction of the population to signal talent by completing college, resulting in degrees being a better signal about talent. In a dynamic environment with skill-biased technical change, as college becomes more accessible along the growth path, the signaling mechanism helps generate part of the increase in the skill premium. When I assess the contribution of signaling from the model for the US economy from 1980 to 2003, I find that a moderate but sizeable 15% of the observed increase in the skill premium can be attributed to the signaling mechanism. This is achieved after adjusting for the potential decline of the quality of college graduates.

Keywords: College wage premium; education signal; skill-biased technical change; skill premium; compositional change.

JEL Classification Numbers: D31, E24, I24, J31

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1 Introduction

The rise in the skill premium - defined as the ratio between the wage of college graduates and the wage of high school graduates - especially among the younger US workers since 1980 is a well-documented fact (Autor et al. [2008]; Card and DiNardo [2002]; Eckstein and Nagypal [2004]). The simultaneous rise in the price and supply of skilled labor relative to unskilled labor suggests a demand shifter for skill in the aggregate production function that outpaces the increase in supply to reward skill (or equivalently a college degree) with a higher price. In the literature this process is termed the skill-biased technical change or the SBTC hereafter (Acemoglu [1998], Katz and Murphy [1992], Bound and Johnson [1992]). In search for the empirical content of this theory, Krusell et al. [2000], or KORV hereafter, show that the SBTC can be interpreted as embodied in the fast-growing stock of capital equipment which is more complementary to skilled than unskilled labor, generating an increasing demand for skill.

Complementary to the aforementioned demand-side explanations, this paper formalizes and evaluates a supply-side explanation. To the extent that skilled labor is "produced" by completing college, how a college degree signal is interpreted will also affect the return to college degrees. If the increase in the supply of skilled labor relative to unskilled labor is a result of increased access to college and college degrees serve as a signal of talent which is also productive at the workplace, then improved access to college will make college degrees an increasingly clear signal about talent and reward the college graduates an increasingly higher wage premium.

More specifically, how a college degree should be interpreted and rewarded depends on the nature of the hurdles one must overcome to reach it. Imagine a world where agents differ in talent and wealth and college discriminates talent by awarding college degrees to more talented agents with higher probabilities. If access to college is restricted to a small group of wealthy agents, then the group of agents who do not possess a college degree will mostly consist of those who do not have access to college. In this case, the expected talent reflected in a college degree will depend on the distribution of talent among the wealthy subject to the college talent discrimination technology, while the expected talent reflected in a high school diploma will be very close to the average talent in the population. As the economy grows, agents become wealthier and college becomes more accessible, more agents will be able to attend college and signal talent by completing college. Now the expected talent contained in a college degree reflects the distribution of talent of the growing rich, but the expected talent contained in a high school diploma will be a lot lower than the average talent since those with only a high school diploma are more likely to be those who fail college.

In a stationary environment in which the distribution of talent conditioning on college attendance does not change along the growth path, the increase in college premium from improved access is due to a decrease in the expected talent of high school graduates.[1] In a more general environment with technological change and productivity growth, the increase in college premium is due to the fact that the wage of high school graduates grows less than the average and a lot less than that of college graduates. The implication of this thought experiment on the US economy is that if college enrollment increased because college education has become more accessible, then I should have observed also an increase in the college wage premium. [2]

In this paper, I incorporate an explicit signaling mechanism into a neoclassical aggregate production function with three inputs: capital, skilled and unskilled labor. By doing so, the efficiency unit of skilled and unskilled labor, usually interpreted as the factor-specific productivity in the SBTC literature, has a direct structural interpretation as the expected talent of college and high school graduates. As more people can afford and choose to attend college, the supply of skilled labor in this economy grows. At the same time, the signaling mechanism, by the intuition explained above, implies an increase in the differential of the expected talent of college graduates and that of high school graduates, resulting in an upward pressure on the skill premium. I will make the intuition precise in a dynamic model with closed-form solutions for the equilibrium path.[3] Then I will evaluate the contribution from this signaling mechanism on the growth of skill premium in an example of the US economy from 1980 to 2003. During this period, the US saw an increasing trend in both college enrollment rates and the college wage premium (Figure 1).

The theoretical and quantitative work suggests that the signaling mechanism I model is unlikely to be the sole driver of the skill premium, yet it has a sizeable effect on the US economy, accounting for about 15% of the increase in the college wage premium over the sample period. This estimated contribution from signaling is obtained after adjusting for the decline of the quality of college graduates as found by Carneiro and Lee [2011]. More specifically, Carneiro and Lee show that increased enrollment in US colleges have

[1] The earnings of the unskilled American men saw a dramatic drop in real terms in the 1970s and 1980s (Blackburn et al. [1990]), and did not start to pick up until mid-1990. This is a period in which the increase in skill premium is driven mostly by a deteriorating wage offer to unskilled labor than an increasing wage offer to skilled labor.

[2] The improved access to college can come from many sources, such as an increased supply of college (Juhn et al. [2005]), increased access to financing opportunities including private lenders (Lochner and Monge-Naranjo [2012]), a more education-friendly family environment (Cameron and Heckman [2001] and Carneiro and Heckman [2002]), increased affordability of college (Baumol and Blackman [1995]; Hill et al. [2005]; Archibald and Feldman [2008]) and so on.

[3] Similar intuition is also exploited by Hendel et al. [2005] and more recently by Balart [2010], who consider the implication from increased access to the student loan market on the steady-state level of inequality in a dynamic asymmetric information model. In contrast, I consider the price dynamics of skilled and unskilled labor along the entire growth path of a dynamic production model to examine the evolution of the inequality.

resulted in a decline of the quality of college graduates over the 1960 to 2000 period. If the quality of the college graduates had been fixed at the 1960 level, the skill premium would have grown 30% more by the end of their sample period. In comparison, I model the signaling mechanism explicitly and when assessing my model quantitatively, I use their finding to calibrate the evolution of the expected talent of college graduates.

[Figure 1 about here.]

This paper contributes to the debate on the source of the increase in the college wage premium in the post-1980 US economy. Apart from the aforementioned demand-side explanations, Card and Lemieux [2001], within a supply and demand framework, attribute the increase in the college premium for younger workers to a decrease in the supply of skill from younger workers relative to older workers as a result of the slow-down of the educational attainment of younger cohorts. He [2012] calibrates a general equilibrium overlapping generations model that features both investment-specific technological change (ISTC), which shifts the relative demand for skill, and the demographic change, which affects the relative supply of skill. He finds that the ISTC is a more important factor than the demographic change in driving the skill premium in the postwar US economy (see also He and Liu [2008]). Based on a human capital interpretation of higher education, Guvenen and Kuruscu [2012] examine the human capital accumulation decision in a model with SBTC and heterogeneous agents who differ in the ability to accumulate human capital. I contribute to the discussion by formally introducing the signaling aspect of education into a model with SBTC and show that net of the quantity effects, the change of the content of degree signals can also contribute to the rise of the college premium.

The paper is organized as follows. Section 2 contains the theory: Section 2.1 introduces a static model to highlight the basic intuition; Section 2.2 builds a dynamic model of production with education signals; Section 2.3 presents a theoretical upper bound and lower bound on the signaling effect. In Section 3, I evaluate this model quantitatively for the US economy from 1981 to 2003. The conclusion follows.

2 Theoretical Framework

2.1 A Static Model: the Working of the Education Signal

A static model may help the reader's intuition. Assume personal talent is private information that is nevertheless useful in production. Firms can base their wage offer only on the observable signal, which consists of having attained, or not, a college degree. Everyone holds a high school diploma initially in this model. The population has size one, half is endowed with high talent, $\overline{\theta}$, and half with low talent, $\underline{\theta}$. Let the distribution of wealth in the population be $F(k)$. College education has a fixed cost of Q. Assume that all those with wealth $k \geq Q$ go to college, hence, the fraction of people who goes to college is $1-F(Q)$. Assume there is randomness in successfully completing college. The probability of a high (low) talent person to complete college is $\overline{p}$ ($\underline{p}$), with $\overline{p} > \underline{p}$. The wage offer is simply the expected talent conditional on the signal received. With some algebra, the wage offer to college graduates, $\overline{W}$, and to high school graduates, $\underline{W}$, are

$$\overline{W} = \frac{\overline{p}}{\overline{p}+\underline{p}}\overline{\theta} + \frac{\underline{p}}{\overline{p}+\underline{p}}\underline{\theta}. \tag{1}$$

$$\underline{W} = \frac{1-\overline{p}(1-F(Q))}{2-(\overline{p}+\underline{p})(1-F(Q))}\overline{\theta} + \frac{1-\underline{p}(1-F(Q))}{2-(\overline{p}+\underline{p})(1-F(Q))}\underline{\theta}. \tag{2}$$

While $\overline{W}$ is a constant, $\underline{W}$ depends on the fraction of people that can afford to go to college. Write $x = 1-F(Q)$, I have $W'(x) < 0$, implying that the wage differential increases together with college attendance. Next I embed this simple mechanism in a dynamic model of production.

2.2 Embedding the Education Signal in a Dynamic Model

This is a continuous time discrete choice problem. The economy is populated by a unit measure of dynastic families. Each dynasty is characterized by the pair (θ, k_0), where θ is the time-invariant talent, distributed over $[0, \overline{\theta}]$ according to a cumulative distribution function $G(\theta)$ in the population, and k_0 is the endowment of capital at time 0, distributed over $[0, \overline{k}_0]$ according to a cumulative distribution $F(k_0)$ in the population. The distributions of initial endowments $G(\cdot)$ and $F(\cdot)$ are independent.[4] An agent at t is indexed by the dynasty that he belongs to,(θ, k_0).[5] Each agent is endowed with 1 unit of labor, is risk neutral and maximizes the discounted sum of future consumption in his dynasty:

$$U(t;\theta,k_0) = \int_t^\infty c(\tau;\theta,k_0)e^{-r\tau}d\tau. \tag{3}$$

[4]Even though the initial endowments of talent and capital stocks are independent, along the equilibrium path, talent and capital holdings will in general be correlated.

[5]For simplicity we take talent θ as a time-invariant attribute of a dynasty. This is without loss of generality in the type of equilibrium that we consider.

At each instant, an agent faces a discrete choice of whether going to college or not. If he chooses to go to college, he pays a fixed cost Q, after which he either completes college or not. The probability of completing college is higher for agents with higher talent. This is summarized in the probability of college completion $p(\theta)$, which satisfies $p'(\theta) > 0$ and $p(\theta) > 0$, for all $\theta \in [0, \overline{\theta}]$. Depending on the educational outcome, he goes to the labor market either as a college graduate or a high school graduate. All those who choose not to go to college enter the labor market as high school graduates. Since there is no disutility from labor, all agents supply 1 unit of labor inelastically. There is no capital depreciation. They work, earn wages, receive rental income from the capital, consume and save a constant fraction ϕ of their total income for the next agent in the dynastic family. I only consider positive savings. In other words, intergenerational transfer can be made from the old generation to the young generation only.

Competitive firms hire workers and rent capital for production at each instant. A worker's talent is productive. It is modeled as the efficiency unit per unit labor supply in the production function. Firms however do not observe talent, but only observe the educational outcome. Hence the wage offered to all college (or high school) graduates is the same and reflects the average talent firms believe the college (or high school) graduates have at the time. Following the tradition, skilled (or unskilled) labor and college (or high school) graduates are used interchangeably.

2.2.1 The Agents' Problem

At each instant of time t, an agent from dynasty (θ, k_0) makes the schooling decision to maximize the discounted sum of future consumption of his dynasty, taking the rental rate of capital $R(t)$, the wage of skilled labor $\overline{W}(t)$ and the wage of unskilled labor $\underline{W}(t)$ as given. Denote the value function of an agent (θ, k_0) with a current capital holding $k(t)$ as $v(k(t); \theta, k_0)$. Write the choice-specific value functions as $v^c(k(t); \theta, k_0)$ for college-goers and $v^{nc}(k(t); \theta, k_0)$ for non-college-goers. I have

$$\begin{aligned} rv^c(k(t); \theta, k_0) = p(\theta)\{(1-\phi)[R(t)(k(t)-Q) + \overline{W}(t)] + \frac{dv}{dk}\phi[R(t)(k(t)-Q) + \overline{W}(t)]\} \\ + [1-p(\theta)]\{(1-\phi)[R(t)(k(t)-Q) + \underline{W}(t)] + \frac{dv}{dk}\phi[R(t)(k(t)-Q) + \underline{W}(t)]\} \end{aligned} \tag{4}$$

subject to $k(t) \geq Q$,

$$rv^{nc}(k(t); \theta, k_0) = (1-\phi)[R(t)k(t) + \underline{W}(t)] + \frac{dv}{dk}\phi[R(t)k(t) + \underline{W}(t)], \tag{5}$$

and

$$v(k(t);\theta,k_0) = max\{v^c(k(t);\theta,k_0), v^{nc}(k(t);\theta,k_0)\}. \tag{6}$$

For ease of exposition, the time argument is suppressed when it does not cause confusion. All proofs are collected in the Appendix. I have the following two observations.

Lemma 1. *If it is optimal for an agent with talent θ to go to college at t, then it is optimal for any agent who has talent greater than θ to go to college at t as long as going to college is feasible for him:*

$$k(t;\theta,k_0) \geq Q. \tag{7}$$

Intuitively, for an agent with talent θ, attending college is convenient if the net benefit from attending college

$$p(\theta)(\overline{W} - \underline{W}) - RQ \tag{8}$$

is positive. The net benefit from attending college is the difference between the expected skill premium and the cost of funding a college education. Lemma 1 follows immediately from the assumption that $p(\theta)$ is increasing in θ.

Lemma 2. *If an agent from a dynasty with initial capital endowment k_0 can afford college at t, agents from this dynasty can always afford college at t' greater than t. The fraction of agents who can afford college is increasing in t.*

Under a positive saving rate and zero capital depreciation, the rate of capital accumulation is always positive for all dynasties. Lemma 2 follows naturally.

2.2.2 Production

The production is described by a standard neoclassical production function. It has three inputs: capital k, unskilled labor u and skilled labor s. I consider a nested CES production function to allow for different elasticities of substitution between the inputs:

$$Y(k,u,s) = A\{\mu k^{\sigma} + (1-\mu)[\lambda u^{\rho} + (1-\lambda)s^{\rho}]^{\frac{\sigma}{\rho}}\}^{(1/\sigma)}; \tag{9}$$

where $u = \psi_u h_u$ and $s = \psi_s h_s$ with ψ_u (ψ_s) being the efficiency unit of unskilled (skilled) labor and h_u (h_s) being the quantity of raw unskilled (skilled) labor input. In our setting, h_u (h_s) is taken to be the fraction of high school (college) graduates and ψ_u (ψ_s) the expected talent of high school (college) graduates. The skill premium π, the ratio between the wages of skilled and unskilled labor, is

$$\pi = \frac{1-\lambda}{\lambda}(\frac{h_u}{h_s})^{1-\rho}(\frac{\psi_s}{\psi_u})^{\rho}; \tag{10}$$

Imagine all inputs are functions of time, I can decompose the growth of skill premium into several terms. Let g_x denote the growth rate of x.

$$g_{\pi} = (1-\rho)(g_{h_u} - g_{h_s}) + \rho(g_{\psi_s} - g_{\psi_u}). \tag{11}$$

The component associated with the growth of the quantity of unskilled relative to skilled labor is the relative quantity effect, and the component associated with the growth of the quality of skilled relative to unskilled labor is the relative efficiency effect. The signaling mechanism considered in this paper provides a structural interpretation of how the relative efficiency effect changes over time. In other words, if the increase in the proportion of college graduates is brought by improved access to college, then the increase in the relative supply of skilled labor will be accompanied by an increase in the relative efficiency of the skilled labor. As long as ρ (σ) is positive, or the elasticity of substitution between the skilled and unskilled labor greater than 1, the relative efficiency effect will help generate at least part of the skill premium.

2.2.3 Equilibrium

Definition (Equilibrium)**.** *An equilibrium of this economy is a list of consumption, capital stock and enrollment status* $\{c(t;\theta,k_0), k(t;\theta,k_0), e(t;\theta,k_0)\}_{t=0}^{\infty}$ *for each agent from dynasty* (θ,k_0) *and a list of prices* $\{R(t), \overline{W}(t), \underline{W}(t)\}_{t=0}^{\infty}$*, given the initial distribution of capital* $F(\cdot)$ *over* $[0,\bar{k}_0]$ *and the distribution of talent* $G(\cdot)$ *over* $[0,\bar{\theta}]$*, the positive saving rate* ϕ *and the production technology* $Y(k,u,s)$*, so that (i) All agents* *optimally make schooling decision*

$$e(k(t;\theta,k_0)) = \begin{cases} 1, & \textit{if } (\theta,k_0) \textit{ attends college at } t \\ 0, & \textit{otherwise.} \end{cases} \tag{12}$$

(ii) Firms maximize the current period profit; (iii) Factor markets clear: for all t,

$$K(t) = \int_0^{\bar{\theta}} \int_0^{\bar{k}_0} [k(t;\theta,k_0) - e(k(t;\theta,k_0))Q]dF(k_0)dG(\theta); \tag{13}$$

$$1 = h_s(t) + h_u(t). \tag{14}$$

I focus on a type of the equilibrium which is separating only in terms of the initial wealth. Call it a *wealth-separating equilibrium*. Along the path of a wealth-separating equilibrium, whose existence I will shortly turn to, as the economy grows and agents accumulate capital, the selection effect from wealth on schooling will bring about changes in the average efficiency units of skilled and unskilled labor, contributing to the dynamics of skill premium. In a wealth-separating equilibrium, all agents optimally go to college as soon as college becomes feasible:

$$e(k(t;\theta,k_0)) = \begin{cases} 1, & k(t;\theta,k_0) \leq Q \\ 0, & k(t;\theta,k_0) > Q \end{cases} \tag{15}$$

One immediate implication from Lemma 2 is that in the wealth-separating equilibrium, since the schooling decision only depends on one's financial means, agents from initially wealthier dynasties start going to college earlier than agents from initially poorer dynasties. Moreover, once a dynasty starts attempting college it will keep doing so and hence there will be a growing fraction of agents attending college. Let $x(t)$ denote the fraction of agents going to college at time t. Let $\widehat{k}_0(t)$ denote the initial wealth endowment of the dynasty whose agent attends college for the first time at t. From Lemma 2 and (15),

$$x(t) = 1 - F(\widehat{k}_0(t)). \tag{16}$$

Given the environment and the definition of the wealth-separating equilibrium, we can write the quantity and efficiency of skilled and unskilled labor for a given enrollment rate $x(t)$ as

$$h_s(t) = x(t)\int_0^{\bar{\theta}} p(\theta)dG; \tag{17}$$

$$\psi_s(t) = E_t(\theta|s) = \frac{\int_0^{\bar{\theta}} \theta p(\theta)dG}{\int_0^{\bar{\theta}} p(\theta)dG}; \tag{18}$$

$$h_u(t) = 1 - x(t)\int_0^{\bar{\theta}} p(\theta)dG; \tag{19}$$

$$\psi_u(t) = E_t(\theta|u) = \frac{\int_0^{\bar{\theta}} \theta dG - x(t)\int_0^{\bar{\theta}} \theta p(\theta)dG}{1 - x(t)\int_0^{\bar{\theta}} p(\theta)dG}. \tag{20}$$

It is clear that the supply of skilled labor increases and that of unskilled labor decreases whenever the enrollment rate increases; on the other hand, the efficiency of skilled labor remains constant and that of unskilled labor deteriorates whenever the enrollment rate increases. In other words, I have the relative quantity effect, $(1-\rho)(g_{h_u} - g_{h_s})$, to be negative and the relative efficiency effect, $\rho(g_{\psi_s} - g_{\psi_u})$, to be positive for any ρ greater than 0 and on any path that has increasing enrollment rates. If I find an environment in which the schooling decision (15) is indeed optimal under the equilibrium factor prices and the relative efficiency effect dominates the relative quantity effect, then I have constructed a wealth-separating equilibrium in which both the skill premium and the college enrollment rate increases over time. This is achieved in Proposition 1.[6]

Proposition 1. *For sufficiently high ρ, sufficiently low λ and Q, there exists a wealth-separating equilibrium where the college enrollment rate increases together with the skill premium.*

The exact restrictions on the parameters can be found in the proof, but a few comments on the restrictions are warranted here. To ensure that the skilled labor is always paid a higher wage than the unskilled labor, I need the share of output contributed by unskilled labor to be sufficiently small relative to the share of output contributed by skilled labor. This translates into the parametric restriction on the share parameter λ:

$$\lambda < \frac{1}{(\frac{h_s(0)}{h_u(0)})^{1-\rho}(\frac{\psi_u(0)}{\psi_s(0)})^{\rho} + 1}. \tag{21}$$

To ensure that the skill premium increases in the enrollment rate, I need the elasticity of substitution

[6] The author has also established the existence of other types of dynamic equilibrium in which the equilibrium is separating both in wealth and talent. However, it is ambiguous how the skill premium evolves along the equilibrium path given an increasing trend of the college enrollment rate. The proof of existence and characterization of these equilibria are available from the author upon request.

between the skilled and unskilled labor to be sufficiently large (and necessarily larger than 1):

$$\frac{1}{1-\rho} \geq 1 + \frac{\int_0^{\overline{\theta}} \theta dG - x(0)\int_0^{\overline{\theta}} \theta p(\theta) dG}{x(0)(\int_0^{\overline{\theta}} \theta p(\theta) dG - \int_0^{\overline{\theta}} p(\theta) dG \int_0^{\overline{\theta}} \theta dG)}, \tag{22}$$

or,

$$\frac{1}{1-\rho} \geq 1 + \frac{h_u(0)}{h_s(0)} / [\frac{E(\theta|s)}{E_0(\theta|u)} - \frac{E(\theta)}{E_0(\theta|u)}]. \tag{23}$$

It suggests that if the college sends a very discriminating signal in the sense that the $p(\theta)$ rises steeply at larger θ, then it is more likely that I will have $E(\theta|s)$ much bigger than $E(\theta)$ as well as $E(\theta|u)$ relatively low. In this case, the relative efficiency effect can overcome the relative quantity effect for relatively low substitution elasticities. In the next section, I examine formally the implication of various values of ρ on the evolution of the skill premium within the structure of the model.

For any value of λ and ρ satisfying the above restrictions, I can find an upper bound of college cost $\hat{Q}$ so that as long as the cost of college in the model falls below $\hat{Q}$ agents of all talent find attending college optimal. In this wealth-separating equilibrium, the change in the skilled and unskilled labor supply is governed by the change in the enrollment rate, which is in turn pinned down by the cut-off in the initial wealth $\widehat{k}_0(t)$. Therefore, the equilibrium path can be completely characterized by a dynamic system in two variables, the aggregate capital $K(t)$, and the cut-off wealth level, $\widehat{k}_0(t)$:

$$\begin{cases} \dot{K}(t) = \phi Y(K(t) - x(t)Q, 1 - x(t)\int_0^{\overline{\theta}} p(\theta) dG, x(t)\int_0^{\overline{\theta}} p(\theta) dG) \\ \dot{\widehat{k}}_0(t) = -\phi[R(t)Q + \underline{W}_t] \end{cases} \tag{24}$$

$$\text{where } x(t) = 1 - F(\widehat{k}_0(t)),$$
$$\text{s.t. } \widehat{k}_0(t) \geq 0, \text{ with } K(0) = \int_0^{\bar{k}_0} k_0 dF(k_0) \text{ and } k_0(0) = Q.$$

2.3 A Theoretical Bound of the Effect of the Education Signal

Given our wealth-separating equilibrium, the next question is how much this mechanism can account for the growth in the skill premium. Within the structure of the model, the relative efficiency effect depends not only on the observed college enrollment rates but also on the unobservable distribution of talent $G(\cdot)$ and the college completion probabilities $p(\cdot)$. In this section, I transform the problem and derive a theoretical upper bound and lower bound on the relative efficiency effect. In other words, I ask how much growth in the skill premium can the signaling mechanism generate when the unobservable behave in the most favorable way (i.e. the upper bound) and in the least favorable way (i.e. the lower bound). With these theoretical bounds, I hope to address two concerns. One, it is a theoretical response to a widely held view that compositional changes in the labor force have little effect on the distribution of wages. Two, it sheds light on the determinants of the magnitude of the signaling effect. Recall from Section 2.2.2 that the growth rate of the skill premium can be decomposed exactly into two components, the relative quantity effect and the relative efficiency effect:

$$g_\pi = (1-\rho)(g_{h_u} - g_{h_s}) + \rho(g_{\psi_s} - g_{\psi_u}). \tag{25}$$

Since the efficiency-unit-unadjusted labor supply h_u and h_s are observable, it is natural to ask whether the structure of the model implies a bound on $g_{\psi_s} - g_{\psi_u}$, which for a given estimate of ρ determines the maximum and minimum growth in skill premium that this model can produce. For the upper bound, I choose the underlying parameters $G(\cdot)$ and $p(\cdot)$ to maximize $g_{\psi_s} - g_{\psi_u}$, while for the lower bound, I aim to minimize $g_{\psi_s} - g_{\psi_u}$:

$$\sup_{\substack{G_t(\cdot)\\ p_t(\cdot)}} (or\ \inf) \frac{\int_0^{\bar{\theta}} \theta p_t(\theta) dG_t - \int_0^{\bar{\theta}} p_t(\theta) dG_t \int_0^{\bar{\theta}} \theta dG_t}{(1 - x(t)\int_0^{\bar{\theta}} p_t(\theta) dG_t)(\int_0^{\bar{\theta}} \theta dG_t - x(t)\int_0^{\bar{\theta}} \theta p_t(\theta) dG_t)} \dot{x}(t). \tag{26}$$

Firstly, to release the full potential of the signal, I allow $G_t(\cdot)$ and $p_t(\cdot)$ to be time-varying. Secondly, the trend of enrollment rates, $x(t)$ and $\dot{x}(t)$, are taken as given at each instant t, for example as pinned down by the empirical counterpart of these series. These two formulations together make the per-period problem exactly the same. Proposition 2 establishes the theoretical bounds on the relative efficiency effect.

Proposition 2. *Let the average completion rate $\int_0^{\bar{\theta}} p_t(\theta) dG_t$ be bounded from below by η and the ratio of the average talent of college graduates and the population average talent be bounded from below by ξ (greater than 1). Suppose $\eta\xi < 1$. The relative efficiency effect, $\rho(g_{\psi_s} - g_{\psi_u})$, in a wealth-separating equilibrium is bounded by the following:*

$$\rho \frac{\eta(\xi-1)\dot{x}}{(1-x\eta)(1-x\eta\xi)} \leq \rho(g_{\psi_s} - g_{\psi_u}) \leq \rho \frac{\dot{x}}{1-x} = -\rho g_{1-x}. \tag{27}$$

From Proposition 2, notice that the upper bound on the relative efficiency effect can be expressed with the observable enrollment rates only. The lower bound however involves properties of $p_t(\cdot)$ and $G_t(\cdot)$. In particular, if the average completion rate $\int_0^{\overline{\theta}} p_t(\theta)dG_t \geq \eta$ and the expected talent of college graduates relative to the population average talent $\frac{\int_0^{\overline{\theta}} \theta p_t(\theta)dG_t}{\int_0^{\overline{\theta}} p_t(\theta)dG_t} / \int_0^{\overline{\theta}} \theta dG_t \geq \xi$, then the lower bound of the relative efficiency effect is increasing in η and ξ. The proof of Proposition 2 suggests that the signaling can generate a higher growth in the skill premium when the distribution of talent is highly upward skewed and when the college can increasingly effectively discriminate high talent.

With these bounds, the first question I ask is whether the compositional change alone can be the driving source of the growth in skill premium. For that to be true, the relative efficiency effect has to be big enough to overcome the relative quantity effect. The answer to this question is negative for empirically plausible elasticities of substitution between skilled and unskilled labor. In Figure 2, I plot the logged skill premium generated by the model with the maximal relative efficiency effect for ρ equal to 0.5, 0.7 and 0.9:

$$(1-\rho)(g_{h_u} - g_{h_s}) - \rho g_{1-x}, \tag{28}$$

where the quantities of skilled and unskilled labor are calculated as in (17) and (19) with the US data of the college enrollment rates and the college completion rates.[7] The construction of the data is discussed in detail in Section 3.1. I then compare the model predicted skill premium with that in the data.

With a substitution elasticity of 3.3 (or $\rho = 0.7$), the relative efficiency effect, at the maximum, is just strong enough to overcome the relative quantity effect. With a substitution elasticity of 2 (or $\rho = 0.5$), even with the maximal relative efficiency effect, the skill premium predicted from the model is declining.

[Figure 2 about here.]

Even though a positive net effect on the skill premium from the signaling seems to depend crucially on a high value of ρ, recognizing this signaling mechanism can always mitigate the downward pressure on the skill premium from the relative quantity effect. To see this, I allow for an additional trend component in the relative efficiency effect in the model. This leads to the following two semi-reduced form models:

$$g_\pi = (1-\rho)(g_{h_u} - g_{h_s}) + \rho(-g_{1-x} + g_{SBTC1}), \tag{29}$$

$$g_\pi = (1-\rho)(g_{h_u} - g_{h_s}) + \rho\left(\frac{\eta(\xi - 1)\dot{x}}{(1-x\eta)(1-x\eta\xi)} + g_{SBTC2}\right). \tag{30}$$

I set η to be the lowest college completion rate in the data, which is 0.6303, and set ξ to be the lowest

[7] The college completion rates in the data correspond to $\int_0^{\overline{\theta}} p_t(\theta)dG$ in the model (now allowed to be time-varying).

ratio between the wage of skilled labor and the average wage in the data, which is 1.1709. Now I can fit the above two semi-reduced form models by choosing g_{SBTC1} and g_{SBTC2} to minimize the distance between the model skill premium and the data counterpart. Let the skill premium generated by the fitted models be denoted π_1 and π_2.

With the fitted models, I run a simulation where I replace the relative efficiency effects by the residual SBTC only:

$$\widehat{g}_{\pi 1} = (1-\rho)(g_{h_u} - g_{h_s}) + \rho g_{SBTC1}, \tag{31}$$

$$\widehat{g}_{\pi 2} = (1-\rho)(g_{h_u} - g_{h_s}) + \rho g_{SBTC2}, \tag{32}$$

and let the skill premium grow from the initial level in the data at rates $\widehat{g}_{\pi 1}$ and $\widehat{g}_{\pi 2}$. Let the resulting simulated skill premium series be denoted $\widehat{\pi}_1$ and $\widehat{\pi}_2$.

I interpret the difference between $\pi_1(\pi_2)$ and $\widehat{\pi}_1(\widehat{\pi}_2)$ as the contribution from the signaling mechanism in the model with maximal (minimal) relative efficiency effect. Given $-g_{1-x} > \frac{\eta(\xi-1)\dot{x}}{(1-x\eta)(1-x\eta\xi)}$, this implies $g_{SBTC1} < g_{SBTC2}$ and hence I should expect $\widehat{\pi}_1 < \widehat{\pi}_2$. Since the π_1 and π_2 both fit the trend of skill premium well, I should expect the contribution of the signaling mechanism to be bigger in the first than the second model.

In Figure 3, I plot $\log(\pi_1)$ and $\log(\widehat{\pi}_1)$ against the skill premium in the data for ρ equal to 0.4 (or the substitution elasticity between skilled and unskilled labor of 1.67 as reported by KORV). In Figure 4, I plot $\log(\pi_2)$ and $\log(\widehat{\pi}_2)$ against the data for the same ρ.

[Figures 3 and 4 about here.]

I define the measure of the signaling effect as the percentage difference of the logged skill premium generated by the fitted model and that by the model with the residual SBTC as the only source of change in the relative efficiency effect. More precisely, the effect of signaling is measured by

$$\left(1 - \frac{\log(\widehat{\pi}_{iT}) - \log(\widehat{\pi}_{i1})}{\log(\pi_{iT}) - \log(\pi_{i1})}\right) \times 100, \text{ for } i = 1, 2. \tag{33}$$

The time subscript T denotes the last period in the sample and the initial level of skill premium in both models is the same as the initial skill premium in the data: $\pi_{11} = \widehat{\pi}_{11} = \pi_{21} = \widehat{\pi}_{21}$.

In Figure 5, I plot this measure of the signaling effect for both models and for empirically plausible

ρ ranging from 0.29 to 0.5. For example, for ρ equal to 0.4, the effect of signaling from the model with maximal relative efficiency effect is 57.63% and that from the model with minimal relative efficiency effect is 13.03%. As is demonstrated by these simulations, the effect of signaling can range from just over 10% of the observed growth in skill premium to over 50%. The actual contribution of signaling depends on the particular economic environment one is looking at.

[Figure 5 about here.]

To sum up, the results suggest that the signaling mechanism formalized here will not likely generate the entire growth of skill premium in a realistic setting. However they do suggest the type of environment in which the signaling has a bigger effect: for example where the aggregate production function displays a high elasticity of substitution between skilled and unskilled labor, and/or where the college education system becomes increasingly efficient in discriminating high talent.

3 A Quantitative Assessment: US 1980-2003

During the period 1974 to 1997, the US saw a monotonically increasing trend in the college enrollment rates, which provides us with a convenient environment to evaluate the signaling mechanism developed in this paper (Figure 1). Section 2.3 makes it clear that the signaling mechanism is unlikely to be the sole driver of the increase in skill premium. Therefore the proper question to ask is, under reasonable parameter values, how much the signaling mechanism can help generate the observed skill premium. To that end, I estimate a semi-reduced-form model in the spirit of (29) or (30), but retaining the structural elements in the relative efficiency effect.

To be more specific, I incorporate the reduced-form SBTC into the model by replacing the evolution of $\psi_s(t)$ in (18) with [8]

$$\psi_s(t) = e^{(1+\gamma_{SBTC})\cdot t} \frac{\int_0^{\bar{\theta}} \theta p(\theta) dG}{\int_0^{\bar{\theta}} p(\theta) dG}. \tag{34}$$

[8] In the Methodology section 3.2, I use the discrete version of the dynamic system with each period equal to a year in the data. For example, the actual series of the efficiency unit of skilled labor in the simulation is

$$\psi_{st} = (1+\gamma_{SBTC})^t \frac{\int_0^{\bar{\theta}} \theta p(\theta) dG}{\int_0^{\bar{\theta}} p(\theta) dG}.$$

This is the notation I will adopt in Section 3.2.

The parameter γ_{SBTC} in $\psi_s(t)$ is the residual growth rate of SBTC that is needed on top of the contribution from the signal to generate the skill premium. Note that given our choice of production function and our sample period in which the college enrollment rates increase monotonically, the signaling mechanism and the SBTC are the only two sources that drive up the skill premium. The model remains the same as is described in (24) except for the modification in $\psi_s(t)$.

In order to assess the contribution of the signaling mechanism, I first fit the model to the data (according to a procedure specified later) and then use the fitted model to simulate a hypothetical trend of skill premium, keeping the enrollment rate in the efficiency unit of the unskilled labor fixed at the initial enrollment rate:

$$\psi_u(t) = \frac{\int_0^{\bar{\theta}} \theta dG - x_0 \int_0^{\bar{\theta}} \theta p(\theta) dG}{1 - x_0 \int_0^{\bar{\theta}} p(\theta) dG}. \tag{35}$$

Under a stationary environment where $G(\cdot)$ and $p(\cdot)$ are time-invariant, this would imply a fixed efficiency unit of the unskilled labor. The simulated skill premium would in generally rise slower than the predicted skill premium from the fitted model. I interpret the difference in these two trends of skill premium as a measure of the signaling effect in the same way as in (33).

The enrollment rates $x(t)$ and the skill premium $\pi(t)$ in the model have straight-forward data counterparts. The term $\int_0^{\bar{\theta}} p(\theta) dG$ corresponds to the average college completion rate in the population. With the enrollment rate and college completion rate in hand, I can construct the supply of skilled young workers h_s and the unskilled young workers h_u according to (17) and (19). I develop two alternative strategies to pin down $\int_0^{\bar{\theta}} \theta dG$ and $\int_0^{\bar{\theta}} \theta p(\theta) dG$ and discuss the implications of these strategies on our measure of the signaling effect. In what follows, I discuss the data, the methodology and present the results.

3.1 Data

The data is structured to facilitate the interpretation of a period in the model. The model year refers to the year for which the skill premium is calculated. Within the same period in the model, the enrollment rate six years and college completion rate two years before the model year are used. This is to accommodate the fact that the skill premium is calculated for the age group 23-26. The first period in our sample is 1980 and the last is 2003.

Skill premium. To be consistent with the theoretic prediction that later cohorts who are subject to a stronger signaling effect face a higher premium, the calculation of college premium is cohort-based. I computed the wage series using the CPS March data from 1980 to 2003 by age groups and focus on the age group 23-26. Only fullyear fulltime workers that have positive wage and schooling are considered. The skill premium is the ratio between the weekly wage of a college graduate and the weekly wage of a high school graduate. In order to compute the wage rates, I regress the reported weekly wage by gender on dummies of education, geographic region and race. CPS sampling weights are used. The education has five categories: high school dropouts, high school graduates, some college, college graduates and above. The geographical region has four: Northeast region, Midwest region, South region and West region. The race variable has three: white, black and other. The weekly wage of a college graduate (or a high school graduate) is the sample average of the predicted wage for a white worker with an exact college degree (or an exact high school diploma) across geographical regions. I compute the skill premium by gender and by year. Then the skill premium in a given year is obtained by averaging the gender-specific skill premia in that year with the gender-specific aggregate weeks worked as weights. Lastly, we apply the Hodrick-Prescott (HP) filter with a smoothing parameter of 6.25 to this annual series of the skill premium. The construction of the college wage premium essentially follows Autor et al. [2008].

College enrollment rate. The college enrollment and the number of high school completers from 1974 to 1997 are taken from Table 191 "College Enrollment and Enrollment Rates of Recent High School Completers, by sex: 1960 through 2006" in *Digest of Education Statistics 2007*, available on the National Center for Education Statistics (NCES) website. The definition of high school completers is all individuals age 16 to 24 who graduated from high school or completed a GED during the preceding 12 months. The enrollment rate is the ratio between the total enrollment in a given year over the total number of high school completers. HP filter with a smoothing parameter of 6.25 is also applied to this series.

College completion rate. To construct the college completion rate, I take the number of bachelor's degrees conferred by degree-granting institutions each year from 1978 to 2001 and divide it by the total college enrollment four years before. The number of bachelor's degrees conferred by degree-granting institutions by control of institution and by year is taken from Table 266 "Degrees conferred by degree-granting institutions, by control of institution and level of degree: 1969-70 through 2005-06" in *Digest of Education Statistics 2007*. Only bachelor's degrees are counted and the total number is the sum of the number of degrees conferred from public institutions and that from private institutions. The raw data shows a clear upward trend as well as a high volatility. I then regress the raw data on the year and the year squared and use the predicted completion rate instead in the quantitative analysis.

Cost of college. In order to construct the real net cost of college, I need both the sticker price (tuition, fee, room and board, or TFRB) and the total aid per student. The TFRB is reported by types of institution in Table 5 "Average Published Tuition and Fee and Room and Board Charges at Four-Year Institutions in Constant 2009 Dollars, 1979-80 to 2009-10" in *Trends in College Pricing 2009*. I take the enrollment-weighted average of the TFRB in public institutions and in private institutions. The average aid per student is taken from the source data of Figure 11 "Average Aid per Full-Time Equivalent Student in Constant (2008) Dollars, 1973-74 to 2008-09" in *Trends in Student Aid 2009*. The total aid includes grants, loans (excluding private nonfederal loans), federal work-study and education tax benefits. After converting both the TFRB and the aid in constant 2006 dollar, I define the difference between the two as the real net cost of college. The net cost of college has grown only modestly during the 1980 to 2009 period for which I have data (Figure 6). I take the average across years as the empirical counterpart of Q, which is 5444 constant 2006 dollars.

Initial income distribution in 1980. The income distribution in the initial period of the model is proxied by the income distribution in 1980. I take the total family income distribution of all married 40-50 years old males in 1980 from CPS March. These families are likely to have children around 20-year-old in the same year, who face the college attendance decision. Starting from the empirical distribution of family income deflated to constant 2006 dollars, I use the normalized kernel density estimate based on a normal kernel function as the input to the model. The normalization occurs to match the initial enrollment rate of 0.4887 in 1980. More specific, let the income distribution before normalization be denoted $\widehat{cdf}(\cdot)$ and I normalize the income distribution by scaling all income down by a constant ξ, which satisfies $\xi = \frac{\widehat{cdf}^{-1}(1-0.4887)}{Q}$. The resulting income distribution has an income of Q at the 51^{th} percentile. Denote the normalized distribution of family income in 1980 as $cdf(\cdot)$.

In what follows, denote the empirical series of the skill premium, the enrollment rates and the college completion rates as $skpm_t$, $enrl_t$ and $comp_t$.

[Figure 6 about here.]

3.2 Methodology

The general procedure consists of two steps. First, I do a simple calibration exercise for the model described in (24). The calibration proceeds in two nested optimization routines. In the outside loop, I choose the rate of growth of the SBTC, γ_{SBTC}, to minimize the distance between the model generated skill premium and that in the data. In the inside loop, for a given value of γ_{SBTC}, I choose the saving rate ϕ which governs the rate at which the dynasties in the model accumulate capital to minimize the distance between the model generated enrollment rate and that in the data. With the fitted model in hand, in the second step, I simulate the skill premium from this model keeping the enrollment rates in the efficiency unit of the unskilled labor fixed at the initial enrollment rate, i.e. according to (35). Unsurprisingly, the resulting skill premium grows a lot slower than the skill premium generated by the fitted model. The difference between the growth of these two series of skill premium is attributed to the signaling mechanism.

The key parameters of the model are taken from the estimates from the empirical literature:

Model	*Value*	*Interpretation*
ρ	0.4	It implies an elasticity of substitution between skilled and unskilled labor of 1.67 (KORV).
μ	$1/3$	Income share parameter of capital vs aggregate labor.
σ	-1	It implies an elasticity of substitution between capital and aggregated labor of 0.5. (Antras [2004])
λ	0.6	Income share parameter of unskilled labor vs skilled labor.

To simulate the model according to the dynamic system (24), I still need to pin down $\int_0^{\bar{\theta}} \theta dG$ and $\int_0^{\bar{\theta}} \theta p(\theta) dG$. Since I effectively allow $\int_0^{\bar{\theta}} p(\theta) dG$ to vary over time by equating it with the empirical average college completion rate, $comp_t$, I should also allow the possibility for $\int_0^{\bar{\theta}} \theta p(\theta) dG$ to vary over time. To the extent that there is no consensus on an adequate measure of talent for the US during the sample period, to which I can directly calibrate, I decide to determine these series within the model.

Ultimately, the value of $\int_0^{\bar{\theta}} \theta dG$ and $\int_0^{\bar{\theta}} \theta p_t(\theta) dG$ determine: 1) the relative productivity of skilled versus unskilled labor, and 2) the relative productivity of labor versus capital. Point 1) suggests that I determine the ratio $\int_0^{\bar{\theta}} \theta dG / \int_0^{\bar{\theta}} \theta p_0(\theta) dG$ in the initial period by matching the initial level of skill premium in the model with that in the data:

$$skpm_0 = \frac{1-\lambda}{\lambda} \frac{h_{u0}}{h_{s0}} [\frac{s_0}{u_0}]^{\rho} = \frac{1-\lambda}{\lambda} \frac{1 - enrl_0 \cdot comp_0}{enrl_0 \cdot comp_0} (\frac{enrl_0}{\int_0^{\bar{\theta}} \theta dG / \int_0^{\bar{\theta}} \theta p_0(\theta) dG - enrl_0})^{\rho}. \tag{36}$$

Next, given $\int_0^{\bar{\theta}} \theta dG / \int_0^{\bar{\theta}} \theta p_0(\theta) dG$, Point 2) suggests that I solve out $\int_0^{\bar{\theta}} \theta p_0(\theta) dG$ by requiring the capital-labor share of income in the initial period to be $1/2$:

$$\begin{aligned}\frac{1}{2} &= \frac{\mu}{1-\mu}\{\frac{k_0}{[\lambda u_0^{\rho} + (1-\lambda)s_0^{\rho}]^{\frac{1}{\rho}}}\}^{\sigma} \\ &= \frac{\mu}{1-\mu}\{\frac{k_0}{\int_0^{\bar{\theta}}\theta p_0(\theta)dG[\lambda(\int_0^{\bar{\theta}}\theta dG/\int_0^{\bar{\theta}}\theta p_0(\theta)dG - x_0)^{\rho} + (1-\lambda)x_0^{\rho}]^{\frac{1}{\rho}}}\}^{\sigma} \\ &= \frac{\mu}{1-\mu}\{\frac{mean(cdf(\cdot)) - enrl_0 \cdot Q}{\int_0^{\bar{\theta}}\theta p_0(\theta)dG[\lambda(\int_0^{\bar{\theta}}\theta dG/\int_0^{\bar{\theta}}\theta p_0(\theta)dG - enrl_0)^{\rho} + (1-\lambda)\cdot enrl_0^{\rho}]^{\frac{1}{\rho}}}\}^{\sigma}.\end{aligned} \tag{37}$$

Once I have $\int_0^{\bar{\theta}}\theta p_0(\theta)dG$, it is straight-forward to back out $\int_0^{\bar{\theta}}\theta dG$.

Given $\int_0^{\bar{\theta}}\theta p_0(\theta)dG$, I consider two alternative models of how $\int_0^{\bar{\theta}}\theta p_t(\theta)dG$ evolves over time.

Model 1. I let $\int_0^{\bar{\theta}}\theta p_t(\theta)dG$ grow at the same rate as the college completion rates:

$$\int_0^{\bar{\theta}}\theta p_t(\theta)dG = \int_0^{\bar{\theta}}\theta p_0(\theta)dG \cdot \frac{comp_t}{comp_0}. \tag{38}$$

Model 1 respects the tight restriction from the theory that the expected talent of a college graduate remains constant over time:

$$E[\theta|CG] = \frac{\int_0^{\bar{\theta}}\theta p_t(\theta)dG}{comp_t} = \frac{\int_0^{\bar{\theta}}\theta p_0(\theta)dG}{comp_0}. \tag{39}$$

Let the skill premium generated by the fitted model be denoted π_t. With the fitted model, I simulate the hypothetical trend of the skill premium fixing the enrollment rates at the initial level:

$$\widehat{\pi}_t = \frac{1-\lambda}{\lambda}(\frac{h_{ut}}{h_{st}})^{1-\rho}(\frac{\psi_{st}}{\widehat{\psi}_{ut}})^{\rho}, \tag{40}$$

where h_{ut}, h_{st} and ψ_{st} remain as before and $\widehat{\psi}_{ut}$ is given by

$$\widehat{\psi}_{ut} = \frac{\int_0^{\bar{\theta}}\theta dG - x_0\int_0^{\bar{\theta}}\theta p_t(\theta)dG}{1 - x_0 \cdot comp_t}. \tag{41}$$

The difference between $\widehat{\pi}_t$ and π_t defines the measure of the signaling component.

In light of the recent finding by Carneiro and Lee [2011], I feel that requiring the quality of college graduates to remain constant due to a parsimonious theoretical model is somewhat restrictive. Carneiro and Lee show that the average quality of the US college graduates has decreased over the 1960 to 2000 period and the decline has a substantial impact on the evolution of the wage distribution. More specifically, their estimates imply that if the quality of college graduates had been fixed at the 1960 level, the (logged) skill premium would have grown 30% more by 2000. In Model 2, I modify my assumption on the expected talent of college graduates and calibrate its trend to match their result.

Model 2. I calibrate the decrease in the expected talent of college graduates so that with the fitted model, if I had fixed the expected talent of the college graduate at the initial level, the model would generate a trend of the (logged) skill premium that is 17.25% higher than what the fitted model generates.[9] More precisely, I let $\int_0^{\overline{\theta}} \theta p_t(\theta) dG$ vary over time at the rate ω:

$$\int_0^{\overline{\theta}} \theta p_t(\theta) dG = \int_0^{\overline{\theta}} \theta p_0(\theta) dG \cdot (1+\omega)^t, \tag{42}$$

where the growth rate ω is lower than the implied growth rate in the series $comp_t$ so that the average quality of a college graduate decreases over time:

$$E_t[\theta|CG] = \int_0^{\overline{\theta}} \theta p_0(\theta) dG \cdot \frac{(1+\omega)^t}{comp_t}. \tag{43}$$

For each trial of ω, I fit the model as before by first choosing ϕ to fit the enrollment data (for a given γ_{SBTC}) and next choosing γ_{SBTC} to fit the skill premium data. With this model, I simulate the skill premium fixing the quality of college graduates $E_t[\theta|CG]$ at the initial level, $\int_0^{\overline{\theta}} \theta p_0(\theta) dG / comp_0$:

$$\widetilde{\pi}_t = \frac{1-\lambda}{\lambda} (\frac{h_{ut}}{h_{st}})^{1-\rho} (\frac{\widetilde{\psi}_{st}}{\widetilde{\psi}_{ut}})^{\rho}; \tag{44}$$

where h_{ut} and h_{st} remain as before but $\widetilde{\psi}_{st}$ and $\widetilde{\psi}_{ut}$ are given as follows:

$$\widetilde{\psi}_{st} = (1+\gamma_{SBTC})^t \frac{\int_0^{\overline{\theta}} \theta p_0(\theta) dG}{comp_0} \tag{45}$$

$$\widetilde{\psi}_{ut} = \frac{\int_0^{\overline{\theta}} \theta dG - x_t \frac{\int_0^{\overline{\theta}} \theta p_0(\theta) dG}{comp0} comp_t}{1 - x_t \cdot comp_t} \tag{46}$$

I choose the ω such that the (logged) skill premium $\log(\widetilde{\pi}_t)$ is 17.25% higher than the logged skill premium generated by the fitted model. With the choice of ω, I have pinned down all the parameters in the model. Then I follow the same procedure as before to measure the contribution from the signaling.

[9] The number 17.25% is obtained from $30\% \times 23/40$.

Compared with Model 1, I expect it to be more difficulty for this model to generate the skill premium, due to the extra downward pressure on the skill premium from the deteriorating quality of the college graduates. Indeed, the implied residual growth of SBTC is higher for Model 2 than for Model 1.

3.3 Results

The fit of Model 1 in terms of the enrollment rates and the (logged) skill premium is reported in Figures 7 and 8. In Figure 8, the solid blue line is the skill premium generated by the fitted Model 1 over the sample period. Since the model is essentially a theory about the trend of the skill premium, the model does not catch the swing in the skill premium in the late 1980s, yet it is able to match well with the overall increase in the skill premium in the data. The dashed blue line is the prediction of the skill premium from Model 1 fixing the enrollment rates at the initial level in forming the belief of the expected talent of high school graduates. Without recognizing the signaling that comes from the increased college attendance, the model generates an increase of the (logged) skill premium that is only 81.24% of the observed increase.

The fit of Model 2 is likewise presented in Figures 9 and 10. The implied decline in the quality of college graduates (or the expected talent of college graduates) is about 4% of the initial level by the end of the 24 years of the sample period. In Figure 11, the dashed blue line shows the simulated skill premium from the fitted Model 2 fixing the quality of college graduates fixed at the 1980 level. It is 17.25% higher in 2003 relative to the skill premium from the fitted model (the solid blue line). With Model 2, the hypothetical skill premium shutting down the signaling mechanism stands at 84.77% in 2003 of the skill premium from the fitted model (Figure 10).

Comparing Figures 8 and 10 with the bounds of the signaling effect in Figures 3 and 4, the effect of signaling from either model falls close to the theoretical lower bound I established in Section 2.3. As I have expected, the implied growth of SBTC in Model 2 (7.84%) is higher than in Model 1 (7.55%).

From the above exercise, I can conclude that the effect from the signaling mechanism is not overwhelming but significant. It generates about 18.76% of the increase in the observed (logged) skill premium in Model 1 and about a perhaps more realistic 15.23% of the increase in the (logged) skill premium in Model 2, which takes into account the decline of the quality of the college graduates.

[Figures 7 to 11 about here.]

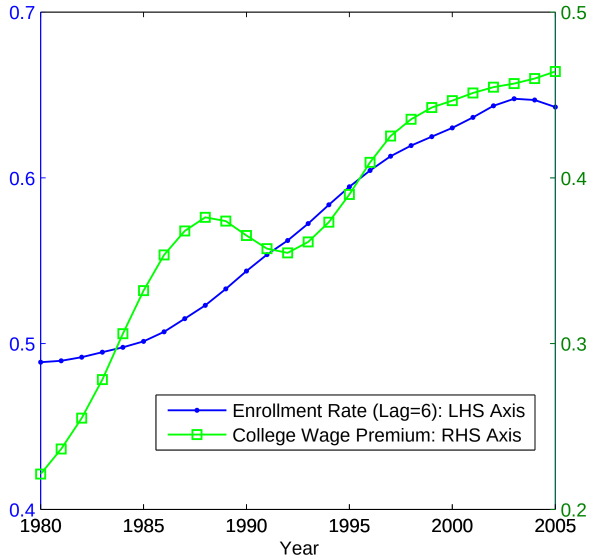
4 Conclusion

Though the idea of education as a job market signal is well known (Spence [1973] and Stiglitz [1975]), its application to the evolution of wage distribution hasn't been well articulated in theory. This paper is such an attempt. I develop a model with agents heterogeneous in initial wealth and talent, who make schooling decisions. The growth in the college enrollment rate due to increased access to college makes a high school diploma a clearer signal of low talent. If talent is useful in production, a college degree will be rewarded a higher premium relative to a high school diploma. This brings about a growing wage gap between college and high school graduates.

I show that the effect from the signaling mechanism I model tends to be strong when the elasticity of substitution between the college educated and non-college educated labor is high and/or when the college sector becomes increasingly efficient in discriminating high talent. However, the theoretical bound on the signaling effect suggests that the signaling mechanism itself is not likely the main driving force of the increase of skill premium.

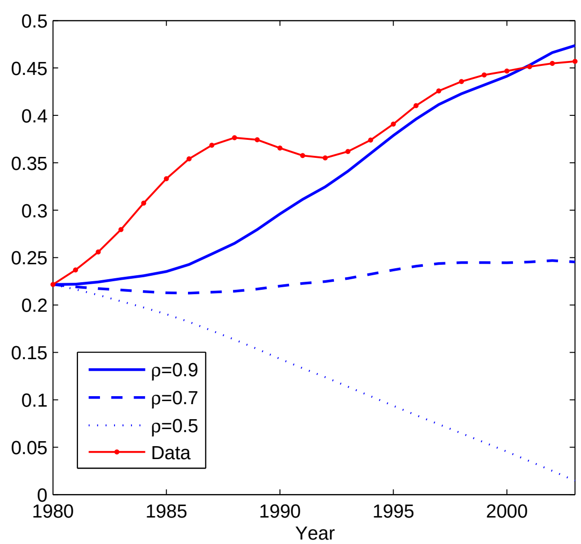
When I calibrate the model to the observed trends in the skill premium for young workers and the college enrollment rates in the US from 1980 to 2003, I find that the signaling mechanism has a modest but sizeable effect on the increase in the college wage premium. In a model that also adjusts for the declining quality of college graduates, the signaling mechanism accounts for 15.23% of the increase in the observed college wage premium over the 24 years in the sample. I interpret my finding as suggesting that we economists should perhaps take a more serious approach to modeling the college sector as the supply of the skilled labor. Compositional changes in the "output" of the college sector can imply revisions to what we have understood as sources of a growing inequality.

Figure 1: HP Filtered Trend of Enrollment Rate and College Wage Premium: 1980-2005



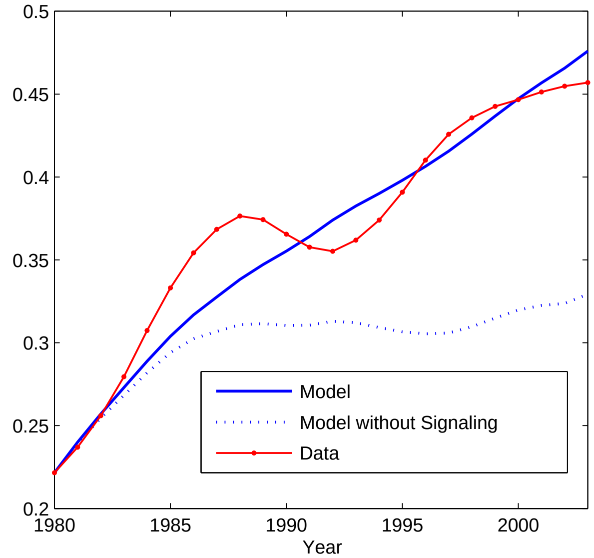
Note:The college wage premium plotted is the log of the ratio of the weekly wage of a college graduate and a high school graduate. The enrollment rates are from *Digest of Education Statistics 2007*. The weekly wage rates are constructed from the CPS March. For the details of the data construction, see Section 3.1.

Figure 2: Skill Premium Generated by the Model with Max Relative Efficiency Effect but without Residual SBTC for High Values of ρ



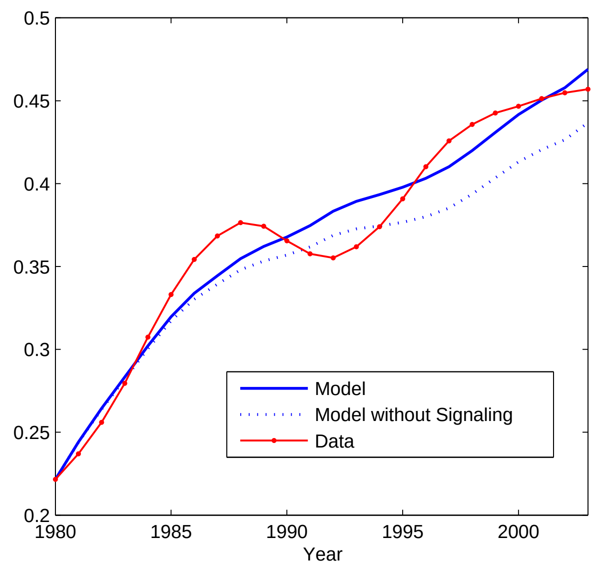
Note: The blue lines are the (logged) skill premium generated from a model with maximal relative efficiency effect and no residual trend in SBTC, or the model (28), for different values of ρ.

Figure 3: Skill Premium from Model with Max Relative Efficiency Effect and Residual SBTC



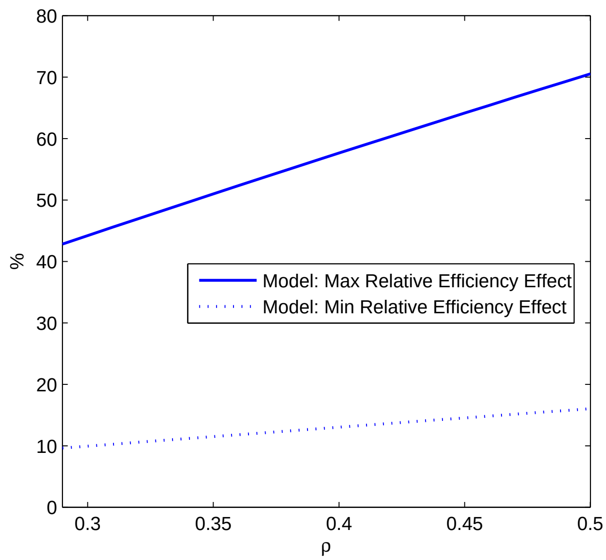
Note: Fix ρ at 0.4. The solid blue line is the (logged) skill premium generated by a model with maximal relative efficiency effect and a residual trend in SBTC, or model (29). The dotted blue line is the (logged) skill premium from the same model replacing the relative efficiency effect by the residual SBTC only.

Figure 4: Skill Premium from Model with Min Relative Efficiency Effect and Residual SBTC



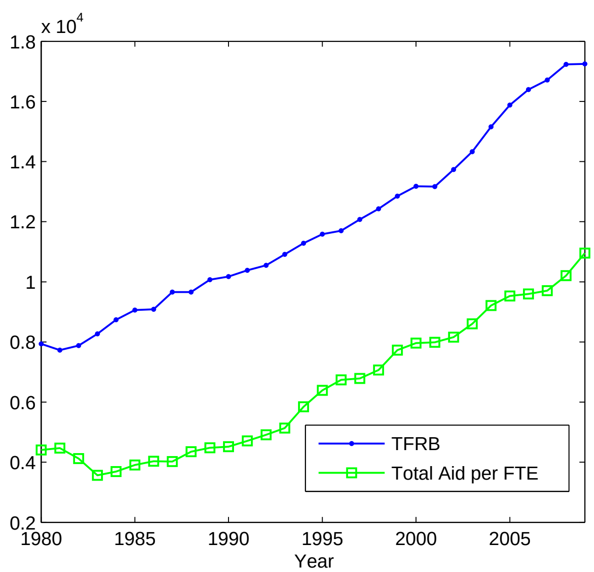
Note: Fix ρ at 0.4. The solid blue line is the (logged) skill premium generated by a model with minimal relative efficiency effect and a residual trend in SBTC, or model (30). The dotted blue line is the (logged) skill premium from the same model replacing the relative efficiency effect by the residual SBTC only.

Figure 5: Percentage of Skill Premium Driven by Changing Relative Efficiency Effect for Various ρ



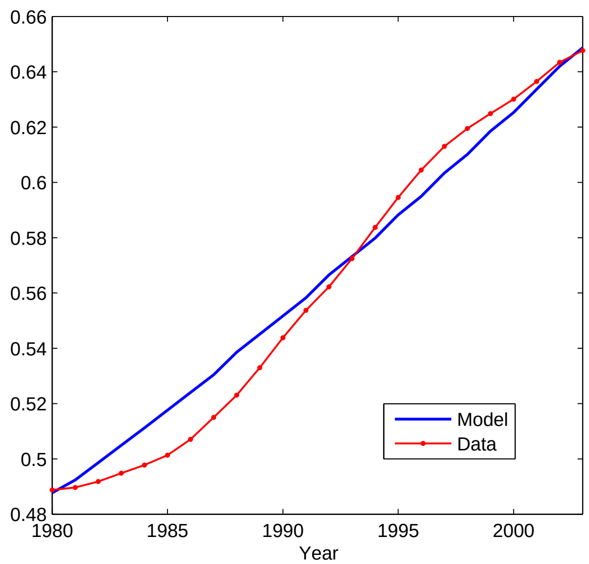
Note: This is the percentage of the (logged) skill premium that is generated by a changing relative efficiency effect, a measure of the signaling effect of this model, for different values of ρ.

Figure 6: Real Tuition, Fees, Room and Board (TFRB) and Total Aid per FTE: 2006$



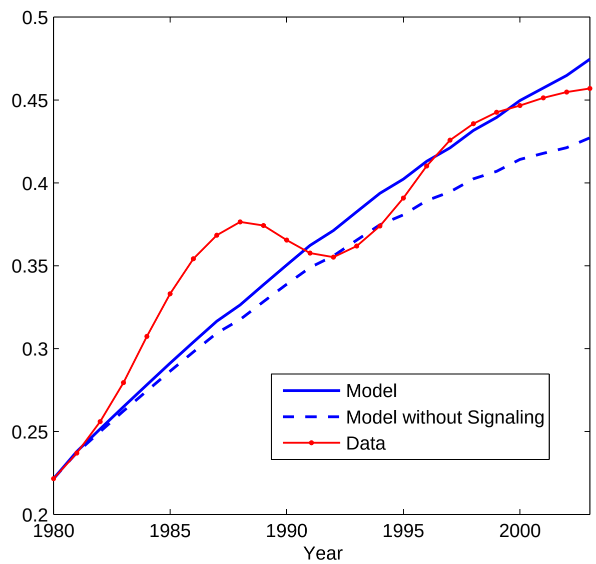
Note: The TFRB is from *Trend in College Pricing 2009* and the total aid per full-time-equivalent student (FTE) is from *Trend in Student Aid 2009*. Both are published by the College Board. For the details of the data, see Section 3.1.

Figure 7: Model 1: Enrollment Rates, Model vs. Data



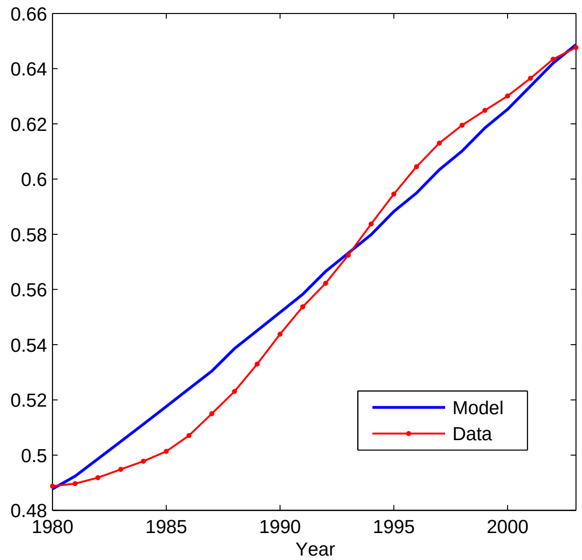
Note: The solid blue line is the endogenous enrollment rates generated by the fitted Model 1.

Figure 8: Model 1: Model Skill Premium with and without Signaling



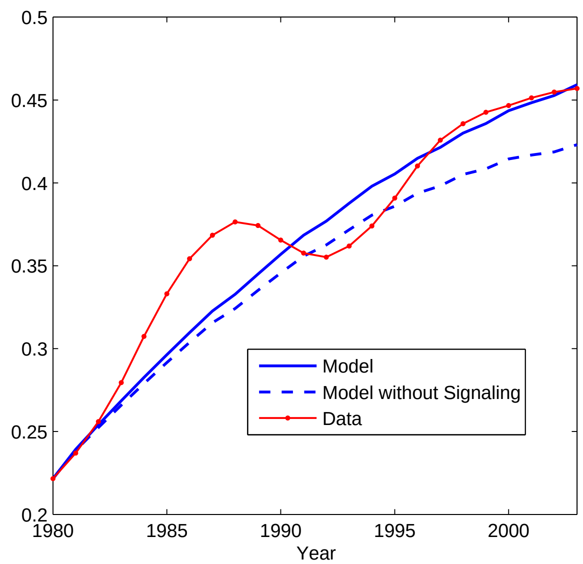
Note: The solid blue line is the (logged) skill premium generated from the fitted Model 1. The dashed blue line is the (logged) skill premium generated from the fitted Model 1 fixing the enrollment rates in the belief of the expected talent of high school graduates at the 1980 level.

Figure 9: Model 2: Enrollment Rates, Model vs. Data



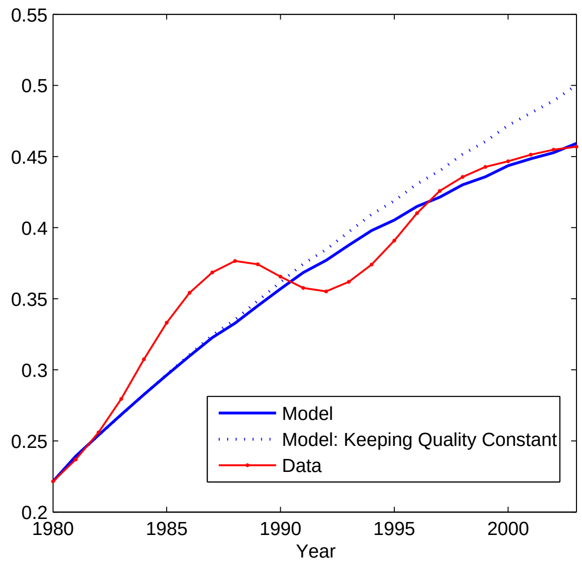
Note: The solid blue line is the endogenous enrollment rates generated by the fitted Model 2.

Figure 10: Model 2: Model Skill Premium with and without Signaling



Note: The solid blue line is the (logged) skill premium generated from the fitted Model 2. The dashed blue line is the (logged) skill premium generated from the fitted Model 2 fixing the enrollment rates in the belief of the expected talent of high school graduates at the 1980 level.

Figure 11: Model 2: Skill Premium, Skilled Labor Quality Adjusted or Not



Note: The solid blue line is the (logged) skill premium generated from the fitted Model 2. The dotted blue line is the (logged) skill premium generated from the fitted Model 2 fixing the expected talent of college graduates in the efficiency units of the skilled and unskilled labor at the 1980 level.

Appendix

Proof of Lemma1.

Proof. Let the net benefit of going to college $\Delta(\theta, k_0)$, be defined as the difference between the choice-specific value functions in (4) and (5), we have

$$\begin{aligned}\Delta(\theta, k_0) &\equiv v^c(k;\theta,k_0) - v^{nc}(k;\theta,k_0) \\ &= (1-\phi+\phi\frac{dv}{dk})[p(\theta)(\overline{W}-\underline{W})-RQ] > 0 \Rightarrow p(\theta)(\overline{W}-\underline{W})-RQ > 0.\end{aligned} \tag{A.1}$$

This immediately implies for all $\theta' > \theta$,

$$\Delta(\theta', k_0) = (1-\phi+\phi\frac{dv(k;\theta',k_0)}{dk})[p(\theta')(\overline{W}-\underline{W})-RQ] > 0. \tag{A.2}$$

That is, independent of k, the agent (θ', k_0) would always prefer college as long as $k \geq Q$. □

Proof of Lemma 2.

Proof. If an agent indexed by (θ, k_0) can afford college at t, then it must be true that $k(t;\theta,k_0) \geq Q$. The law of motion of capital at the individual level is

$$\begin{aligned}\dot{k}(t;\theta,k_0) = \phi\max\{&p(\theta)\overline{W}(t)+(1-p(\theta))\underline{W}(t)+R(t)[k(t;\theta,k_0)-Q], \\ &\underline{W}(t)+R(t)k(t;\theta,k_0)\} \geq \phi[\underline{W}(t)+R(t)k(t;\theta,k_0)] > 0.\end{aligned} \tag{A.3}$$

Since the capital stock at the individual level always grows at a positive rate (under any positive factor prices), once $k(t;\theta,k_0) \geq Q$, then $k(t';\theta,k_0) \geq Q$ for all t' greater than t. □

Proof of Proposition 1.

Proof. The sufficient and necessary condition of the existence of a wealth-separating equilibrium is to guarantee that agents of all talent find attending college attractive so that financial resources become the only hurdle to college enrollment. By *Lemma 1*, it is enough to show that schooling is an optimal choice for the least talented at all time given the equilibrium prices. The least talented prefers college if

$$p(0)[\overline{W}(t)-\underline{W}(t)]\geq R(t)Q. \tag{A.4}$$

It is necessary that $\overline{W}(t)>\underline{W}(t)$ or $\pi(t)>1$ for all t. Since in the equilibrium $\pi(t)$ always increases, it is enough that

$$\pi(0)=\frac{1-\lambda}{\lambda}(\frac{h_u(0)}{h_s(0)})^{1-\rho}(\frac{\psi_s(0)}{\psi_u(0)})^{\rho}>1\Leftrightarrow\lambda<\frac{1}{(\frac{h_s(0)}{h_u(0)})^{1-\rho}(\frac{\psi_u(0)}{\psi_s(0)})^{\rho}+1}, \tag{A.5}$$

where

$$\frac{h_s(0)}{h_u(0)}=\frac{x(0)\int_0^{\overline{\theta}}p(\theta)dG}{1-x(0)\int_0^{\overline{\theta}}p(\theta)dG}\quad\text{and}\quad\frac{\psi_u(0)}{\psi_s(0)}=\frac{\int_0^{\overline{\theta}}\theta dG-x(0)\int_0^{\overline{\theta}}\theta p(\theta)dG}{1-x(0)\int_0^{\overline{\theta}}p(\theta)dG}\frac{\int_0^{\overline{\theta}}p(\theta)dG}{\int_0^{\overline{\theta}}\theta p(\theta)dG}. \tag{A.7}$$

Notice from (11) the growth of the skill premium depends on ρ. In particular, ρ needs to be high enough so the relative efficiency effect from signaling can overcome the relative quantity effect due to the declining marginal products:

$$\begin{aligned}\frac{d\ln\pi}{dx}&=(1-\rho)\frac{d}{dx}\ln\frac{h_u}{h_s}+\rho\frac{d}{dx}\ln\frac{\psi_s}{\psi_u} && \text{(A.8)}\\&=(1-\rho)\frac{d}{dx}[\ln\frac{1-x\int_0^{\overline{\theta}}p(\theta)dG}{x\int_0^{\overline{\theta}}p(\theta)dG}]+\rho\frac{d}{dx}[\ln\frac{1-x\int_0^{\overline{\theta}}p(\theta)dG}{\int_0^{\overline{\theta}}\theta dG-x\int_0^{\overline{\theta}}\theta p(\theta)dG}]\\&=(1-\rho)\frac{-1}{x(1-x\int_0^{\overline{\theta}}p(\theta)dG)}+\rho\frac{\int_0^{\overline{\theta}}\theta p(\theta)dG-\int_0^{\overline{\theta}}p(\theta)dG\int_0^{\overline{\theta}}\theta dG}{(1-x\int_0^{\overline{\theta}}p(\theta)dG)(\int_0^{\overline{\theta}}\theta dG-x\int_0^{\overline{\theta}}\theta p(\theta)dG)}\geq 0\\&\Leftrightarrow\frac{1}{1-\rho}\geq 1+\frac{(\int_0^{\overline{\theta}}\theta dG-x\int_0^{\overline{\theta}}\theta p(\theta)dG)}{x(\int_0^{\overline{\theta}}\theta p(\theta)dG-\int_0^{\overline{\theta}}p(\theta)dG\int_0^{\overline{\theta}}\theta dG)}. && \text{(A.9)}\end{aligned}$$

The elasticity of substitution between skilled and unskilled labor must necessarily be greater than 1 in order for the relative efficiency effect to dominate. The RHS of the above inequality is clearly decreasing in x, therefore a sufficient condition to guarantee a positive growth in the skill premium is

$$\begin{aligned}\frac{1}{1-\rho}&\geq 1+\frac{\int_0^{\overline{\theta}}\theta dG-x(0)\int_0^{\overline{\theta}}\theta p(\theta)dG}{x(0)(\int_0^{\overline{\theta}}\theta p(\theta)dG-\int_0^{\overline{\theta}}p(\theta)dG\int_0^{\overline{\theta}}\theta dG)} && \text{(A.10)}\\&\Leftrightarrow\rho\geq\frac{\int_0^{\overline{\theta}}\theta dG-x(0)\int_0^{\overline{\theta}}\theta p(\theta)dG}{\int_0^{\overline{\theta}}\theta dG-x(0)\int_0^{\overline{\theta}}p(\theta)dG\int_0^{\overline{\theta}}\theta dG}. && \text{(A.11)}\end{aligned}$$

Substituting the factor prices into (A.4), (A.4) is equivalent to

$$p(0)(1-\mu)[\lambda u^{\rho}+(1-\lambda)s^{\rho}]^{\frac{\sigma}{\rho}-1}[(1-\lambda)s^{\rho-1}\psi_s-\lambda u^{\rho-1}\psi_u]\geq\mu(k-xQ)^{\sigma-1}Q. \tag{A.12}$$

Let the LHS of the above inequality be denoted as $\Phi(x)$ and the RHS be denoted as $\Psi(x,Q)$. Consider

$$\Phi(x)=\Psi(x,Q). \tag{A.13}$$

For a given value of x, $\Phi(x)$ is a strictly positive number and $\Psi(x,Q)$ is strictly increasing in Q, with $\Psi(x,0)=0$ and $\Psi(x,Q)\to+\infty$, as $Q\to\frac{k}{x}-$: $\frac{d}{dQ}[\mu(k-xQ)^{\sigma-1}Q]=\mu(k-xQ)^{\sigma-2}(k-\sigma xQ)>0$. Therefore there exists a unique $\widehat{q}\in(0,\frac{k}{x})$ such that (A.13) holds at $\widehat{q}$ for a given x. Write it as $\widehat{q}(x)$. Note that by the continuity of $\Phi(x)$ and $\Psi(x)$, $\widehat{q}(x)$ is continuous in x and strictly positive. Define $\widehat{Q}=\min_{x\in[x(0),1]}\widehat{q}(x)$, which exists. Then for all $Q\leq\widehat{Q}$, the inequality (A.4) holds.

Note that a dynasty starts to send agents to college at t if its initial capital endowment $\widehat{k}_0(t)$ satisfies

$$\widehat{k}_0(t)+\int_0^t\dot{k}(s;\theta,\widehat{k}_0(t))ds=Q, \tag{A.16}$$

where the evolution of $k(t;\theta,k_0)$ follows $\dot{k}(t;\theta,k_0)=\phi[R(t)k(t;\theta,k_0)+\underline{W}(t)]$. Take derivative of (A.16) with respect to t,

$$\widehat{k}_0'(t)=-\phi[R(t)k(t;\theta,\widehat{k}_0(t))+\underline{W}(t)]<0. \tag{A.17}$$

At time t the faction of agents that go to college is $x(t)=1-F(\widehat{k}_0(t))$, which is clearly increasing in t. The equilibrium path can be completely characterized by the dynamic system in the aggregate capital, $K(t)$, and the cut-off wealth level, $\widehat{k}_0(t)$, given in (24). □

Proof of Proposition 2.

Proof. Step 1: Transformation. Let $\widehat{p}(\theta)=\overline{\theta}p(\theta)g(\theta)$, which necessarily satisfies $\widehat{p}(\theta)\geq0$ and $\eta\overline{\theta}\leq\int_0^{\overline{\theta}}\widehat{p}(\theta)d\theta\leq\overline{\theta}$. Let $\int_0^{\overline{\theta}}\theta dG\equiv\mu_\theta$. Then, $\int_0^{\overline{\theta}}\theta\widehat{p}d\theta/\int_0^{\overline{\theta}}\widehat{p}(\theta)d\theta\geq\xi\mu_\theta$. This problem is equivalent to a two-step maximization problem. Given μ_Θ, first solve

$$\sup_{\widehat{p}(\theta)}(\text{or }\inf)\dot{x}\overline{\theta}\frac{\int_0^{\overline{\theta}}\theta\widehat{p}d\theta-\mu_\Theta\int_0^{\overline{\theta}}\widehat{p}d\theta}{(\overline{\theta}-x\int_0^{\overline{\theta}}\widehat{p}d\theta)(\overline{\theta}\mu_\Theta-x\int_0^{\overline{\theta}}\theta\widehat{p}d\theta)} \tag{A.19}$$

$$s.t.\begin{cases}\widehat{p}(\theta)\geq 0\\ \eta\overline{\theta}\leq\int_0^{\overline{\theta}}\widehat{p}(\theta)d\theta\leq\overline{\theta}\\ \xi\mu_\Theta\int_0^{\overline{\theta}}\widehat{p}(\theta)d\theta\leq\int_0^{\overline{\theta}}\theta\widehat{p}d\theta\leq\mu_\Theta\overline{\theta}\end{cases}. \tag{A.20}$$

Then, optimize over all possible μ_Θ.

Step 2: Change of variables. Let $y(\theta)=\int_0^{\theta}\widehat{p}(v)dv$. Integration by part gives $\int_0^{\overline{\theta}}\theta\widehat{p}d\theta=\int_0^{\overline{\theta}}\theta y'(\theta)d\theta=\overline{\theta}y(\overline{\theta})-\int_0^{\overline{\theta}}y(\theta)d\theta$. The problem can be rewritten as

$$\sup_{\substack{y(\overline{\theta}),\\ \int_0^{\overline{\theta}}y(\theta)d\theta}}(\text{or }\inf)\dot{x}\overline{\theta}\frac{(\overline{\theta}-\mu_\Theta)y(\overline{\theta})-\int_0^{\overline{\theta}}y(\theta)d\theta}{(\overline{\theta}-xy(\overline{\theta}))[x\int_0^{\overline{\theta}}y(\theta)d\theta+\overline{\theta}(\mu_\Theta-xy(\overline{\theta}))]} \tag{A.21}$$

$$s.t.\begin{cases}\eta\overline{\theta}\leq y(\overline{\theta})\leq\overline{\theta}\\ y'(\theta)\geq 0\\ \max\{0,\overline{\theta}(y(\overline{\theta})-\mu_\Theta)\}\leq\int_0^{\overline{\theta}}y(\theta)d\theta\leq(\overline{\theta}-\xi\mu_\Theta)y(\overline{\theta})\end{cases}. \tag{A.22}$$

Step 3: Optimization. Firstly, $y(\overline{\theta})$ and $\int_0^{\overline{\theta}}y(\theta)d\theta$ can take values independently. Secondly, the objective is increasing in $y(\overline{\theta})$, but decreasing in $\int_0^{\overline{\theta}}y(\theta)d\theta$. However note that the value of $y(\overline{\theta})$ will affect the boundaries of the values that $\int_0^{\overline{\theta}}y(\theta)d\theta$ can take due to (A.22).

Consider the *sup* problem first. If $y(\overline{\theta})\leq\mu_\Theta$, then the optimal values are $y(\overline{\theta})=\mu_\Theta$ and $\int_0^{\overline{\theta}}y(\theta)d\theta=0$. If $y(\overline{\theta})\geq\mu_\Theta$, then at the optimum, for a given $y(\overline{\theta})$, set $\int_0^{\overline{\theta}}y(\theta)d\theta=\overline{\theta}(y(\overline{\theta})-\mu_\Theta)$. Substituting this equation into the objective function: $\sup_{y(\overline{\theta})}\dot{x}\frac{\overline{\theta}-y(\overline{\theta})}{(\overline{\theta}-xy(\overline{\theta}))(1-x)}$, decreasing in $y(\overline{\theta})$. Hence, at the optimum, $y(\overline{\theta})=\mu_\Theta$ and $\int_0^{\overline{\theta}}y(\theta)d\theta=0$. In both cases, $\sup(g_{\Psi_s}-g_{\Psi_u})=\dot{x}\frac{\overline{\theta}-\mu_\Theta}{(\overline{\theta}-x\mu_\Theta)(1-x)}$. Now maximize the above with respect to μ_Θ: $\sup(g_{\Psi_s}-g_{\Psi_u})=\frac{\dot{x}}{1-x}=-g_{1-x}$, as $\mu_\Theta\to 0$.

Now consider the *inf* problem. For a given $y(\overline{\theta})$, set $\int_0^{\overline{\theta}}y(\theta)d\theta=(\overline{\theta}-\xi\mu_\Theta)y(\overline{\theta})$. Substituting this equation into the objective function: $\inf_{y(\overline{\theta})}\dot{x}\overline{\theta}\frac{y(\overline{\theta})(\xi-1)}{(\overline{\theta}-xy(\overline{\theta}))(\overline{\theta}-x\xi y(\overline{\theta}))}$, increasing in $y(\overline{\theta})$. Hence, setting $y(\overline{\theta})$ to $\eta\overline{\theta}$, I have $\inf(g_{\Psi_s}-g_{\Psi_u})=\frac{\eta(\xi-1)\dot{x}}{(1-x\eta)(1-x\eta\xi)}$. □

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