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UNDERSTANDING THE SUPPLY AND DEMAND FORCES BEHIND THE FALL AND RISE IN THE US SKILL PREMIUM

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I develop an assignment model to quantify, in a unified framework, the causal effects of supply and demand forces on the evolution of the college wage premium in the US economy. Specifically, I quantify the relative contributions of four different forces: (i) a within-sector non-neutral technological change, (ii) the creation of new high-skill services/sectors, (iii) polarizing product demand shifts, and (iv) shifts in the relative supply of skilled labor. The model considers endogenous human capital accumulation. I find that positive supply shifts completely explain the fall of the skill premium during the period 1970–1980. Demand forces play a major role in the post-1980 period, when the skill premium rises. Among the demand forces, the results show an increasing contribution of polarizing product demand shifts over the decades. On the other hand, the effect of the within-sector non-neutral technological change is more important in the earlier decades of the post-1980 period.

Keywords: Skill premium, Technological change, Wage polarization

1. INTRODUCTION

A large literature documents a substantial change in the US wage structure during the past four decades.[1] Changes are observed for different inequality concepts: overall wage inequality, inequality in the upper and lower halves of the wage distribution, between-group wage differentials, and within-group (residual) wage inequality. The literature has paid special attention to the US college wage premium. Figure 1 exhibits the evolution of the college wage premium over the last four decades. We observe that for both men and women the skill premium falls during the pre-1980 period and rises during the post-1980 period.

The evidence exhibited in Figure 1 raises at least three different but related questions. First, what type of framework allows us to understand the movement of the skill premium during the past decades? Second, what are the relative contributions

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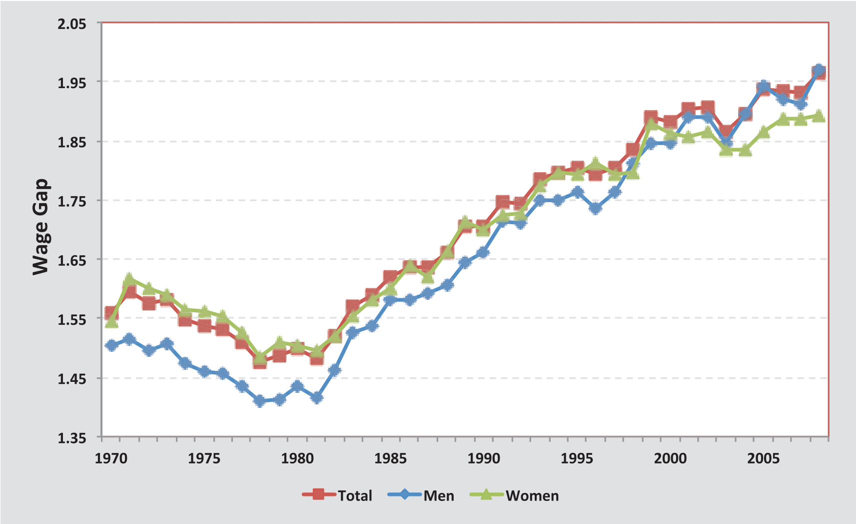

FIGURE 1. College/high-school weekly wage ratio. Source: Acemoglu and Autor (2010).

of supply versus demand forces to those movements in the skill premium? Third, what is the nature of the supply and demand forces moving the skill premium in each decade? Even though the literature has made important progress regarding the first two questions, the third question still remains somewhat elusive; an answer to it requires the analysis of the skill premium in frameworks with a rich structure on either the supply or the demand side of the market (or both). This paper contributes to quantitatively disentangling the nature of the demand forces moving the skill premium across different decades.

I build an assignment model that distinguishes between skills and sectors. A model in which heterogeneous workers are allocated to sectors that differ in their complexity has two characteristics that are important for achieving an identification of demand forces that are of different natures. First, it is flexible enough to model and put in competition several demand forces within the same framework. By doing so, the model allows me to estimate the causal effect of each of those forces in a counterfactual sense. For instance, an assignment model, unlike frameworks that only incorporate technological change in a factor-augmenting form, provides a natural framework for the study of a technological change that might substitute for or replace workers in certain sectors. It also provides a framework for the modeling of labor market polarizing forces. Additionally, a model that distinguishes between skills and sectors allows me to distinguish between demand forces that produce an upgrading within sectors versus a reallocation of workers toward high-skill sectors.

Second, the model allows me to look at data moments of the labor market on which demand forces of different natures have non-isomorphic effects; for

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instance, different parts of the earnings distribution. This aspect is key to identifying the relative quantitative contributions of demand forces that all push the skill premium in the same direction but that are of different natures. Even though two forces, say A and B, can potentially be isomorphic in their effects on the skill premium and the relative demand for college graduates, they can have differentiated impacts on other data moments of the labor market. Those other moments, thus, become "instruments" to achieve the identification of the relative contribution of forces whose impact on the skill premium is completely isomorphic.

This paper is complementary to a large body of empirical research that analyzes the movements in the skill premium within different variants of the so-called canonical supply–demand framework.[2] Compared with that literature, the richer modeling that this paper presents on the demand side allows us to gain a further understanding of the relevant nature of the demand forces moving the skill premium across different decades. This question, in turn, is important for assessing how the current developments in the labor market could impact future inequality trends. It is also important in order to gain an understanding of some phenomena that are related to the movements in the skill premium. For instance, in Parro (2012a), I claim that a change in the nature of the forces behind the demand for education was an important explanation for the worldwide reversal of the gender gap in education.

The pioneering work by Katz and Murphy (1992) proposes a simple supply and demand framework to understand the evolution of the US college wage premium over the past decades. In that framework, the skill premium rises (falls) when the demand for college graduates grows faster (slower) than the supply. Subsequent works have attempted to augment the basic framework by analyzing a richer set of facts [Card and Lemieux (2001a)], refining the data set used [Lemieux (2006)], improving some methodological aspects [Lemieux (2006)], and including non-market factors as determinants of the skill premium [Card and DiNardo (2002)].

The canonical model proposed by Katz and Murphy (1992) and some of the subsequent works have been extremely useful for proving that a standard supply–demand framework is sufficient to understand the movements of the US skill premium. However, they have been less successful in understanding the underlying factors behind the movement of the supply and demand for college graduates. The reason is the lack of structure in their modeling of the supply and demand forces. For instance, in the Katz–Murphy model, the supply of college graduates is assumed to be exogenous and inelastic with respect to the skill premium, and the demand shifts are simply modeled by a linear trend. An exogenous and inelastic supply of college graduates, a linear trend for demand shifts, and an estimated value for the elasticity of substitution between college and high-school "equivalents" produce changes in supply and demand that fit the data very well, at least in earlier decades. However, it is difficult to estimate within that framework the causal effect of different types of forces on the skill premium. What the canonical model and subsequent works do is to seek consistent findings that at most allow them to speculate about the forces behind the supply and demand shifts.[3] Therefore, even though a supply–demand framework can fit the data very well, a further understanding of the underlying forces moving the supply and demand for college graduates is needed. Those forces must be analyzed in a unified framework.

Another strand of the literature quantifies the increase of the skill premium in the US economy in a dynamic general equilibrium framework [Heckman et al. (1998), He and Liu (2008), He (2012), Jones and Yang (2016), among others]. Compared with the canonical model, those articles present a richer structure on the supply side of the market and, thus, go deeper into the modeling of college choices, which determine the supply of skilled workers. However, they do not disentangle the quantitative importance of demand forces of different natures.[4]

A further understanding of the nature of the demand forces pushing up the demand for college graduates requires (i) a framework where different types of demand forces can be put in competition within the same model and (ii) a framework that allows us to analyze different data moments of the labor market on which demand forces of different natures trigger non-isomorphic effects. In this paper, I revisit the analysis of the skill premium with a richer empirical framework on the demand side that meets these requirements. I develop an assignment model to quantify, in a unified framework, the relative contributions of four different forces: a within-sector non-neutral technological change, the creation of new high-skill services/sectors, polarizing product demand shifts, and shifts in the relative supply of skilled labor.

On the demand side, the model captures the distinguishing characteristics of each of the demand forces included in the analysis. The intrinsic nature of each force is reflected in the differential impact they have on different data moments of the labor market. On the supply side, the model follows the theoretical elements highlighted by Cunha and Heckman (2007) and Becker et al. (2010). Human capital accumulation is endogenous and agents are heterogeneous regarding their inherent abilities, which affect their cost of investing in different skills. I explicitly model non-pecuniary costs of investing in higher education. These costs depend negatively on the inherent abilities of agents. In that way, the model includes among the supply factors the "psychic or effort" costs of accumulating human capital. Cunha and Heckman (2007) and Becker et al. (2010) have highlighted the importance of such costs in the investment decisions of agents. Unlike the canonical supply–demand model, the model does not impose a priori an inelastic supply curve. That issue is important since the elasticity of the supply curve partially determines the magnitude of the supply shifts that are needed to explain a given observed change in the skill premium. By calibrating the supply elasticity, I can produce compelling estimates of the magnitude of the supply shifts and, thus, identify the total contribution of supply and demand forces.

I calibrate the model to match data from the US labor market. Psychic costs are calibrated by matching the monetary value of psychic costs paid by the agents in the model with those computed in the literature. I perform counterfactual exercises to estimate the total causal effect of supply and demand forces and the relevant nature of the demand forces behind the skill premium movements across different decades.

The results of this paper show that, on average, 48% of the change in the US skill premium during the last four decades is explained by demand factors. Supply forces explain the remaining 52% of the skill premium variation. Within the demand-driven change in the skill premium, on average, 31% is explained by a polarizing product demand shift within existing sectors, 44% by a skill-biased technological change (SBTC), and 25% by the creation of new high-skill sectors.

Additionally, I find that the relative contribution of each supply and demand force varies across decades. Supply forces play a major role in the 1970–1980 period, when the skill premium falls. Positive supply shifts completely explain the fall of the skill premium during that period. On the other hand, demand forces play a major role in the post-1980 period, when the skill premium rises. The results show an increasing polarization of wages in favor of low- and high-skill workers; the polarization of wages makes a key contribution during the 1990–2000 decade and, to a lesser extent, the 2000–2008 period. The polarization of wages is the result of a product demand shift that reduces the relative demand for middle-complexity services, mostly performed by high-school graduates. During the post-1980 period, the contribution of this force to the rise in the college wage premium goes from 2% in the period 1980–1990 to 36% in 1990–2000 and 27% in the last decade included in the analysis. Additionally, the results show a decreasing contribution of a within-sector non-neutral technological change during the post-1980 period. The contribution of this demand force declines from 60% to 14% over that period.

I also perform two types of sensitivity analysis. First, I evaluate the sensitivity of the main results to changes in the elasticity of substitution between services. Second, I assess how the results change when the variance of the distribution of abilities falls. I study whether the estimated changes in the contributions of supply and demand forces for different elasticities are in line with what economic theory predicts.

I find that as the elasticity of substitution rises, the contribution of demand factors increases. This result is consistent with the fact that a higher elasticity of substitution makes the demand curve for more educated workers more elastic and, thus, greater demand shifts are needed to explain the observed changes in quantities and prices. In contrast, as the variance of the distribution of abilities falls, the contribution of supply forces increases. This is consistent with the fact that a lower variance implies more homogeneous agents and, thus, a more elastic supply curve for more educated workers. With a more elastic supply curve, greater negative supply shifts are needed to explain the rise in the college wage premium in the context of increasing demand for college graduates during the post-1980 period. Analogously, bigger positive supply shifts are needed to explain the fall in the college wage premium in the context of stable demand for college graduates during the pre-1980 period. Therefore, the results of the sensitivity analysis are consistent with the predictions derived from the economic theory.

Overall, this paper shows that putting several demand forces to compete in the same model reveals that the relevant natures of the demand-side channels behind movements in the skill premium are not the same, but vary across decades. This conclusion contrasts with the one derived from a canonical model that only incorporates a technological change in a factor-augmenting form, approximated empirically by a linear trend, and that, thus, assigns a unique nature to the demand forces pushing the skill premium up. From a policy viewpoint, this paper highlights that it is the nature of the labor market forces that in the end determines how labor market developments impact inequality trends when summarized by the skill premium. For instance, from the forces that could have been responsible for shocks to the labor market during the post-1980 period, I have shown that those whose intrinsic nature is polarizing have become more significant during the post-1990 period. Are the new technologies arriving at the workplace going to further increase inequality? What about a complete robotization of life? Looking at the most recent decades, the evidence presented in this paper suggests that over the next decades, those containing a polarizing nature should exert a more significant impact on inequality trends than other forces.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 discusses the calibration strategy. Section 4 presents and discusses the results of the counterfactual exercises. Finally, Section 5 concludes.

2. THE MODEL

In this section, I develop the framework used to quantify the causal effects of different supply and demand forces on the US skill premium. Three types of demand forces are embodied in the production technology of this economy model: (i) a within-sector non-neutral technological change, (ii) the creation of new high-skill services/sectors, and (iii) polarizing product demand shifts. On the supply side, the model considers endogenous human capital accumulation. Agents are heterogeneous regarding their inherent abilities. Their costs of investing in different skills depend negatively on their inherent abilities. I explicitly model non-pecuniary or "psychic or effort" costs of investing in higher education, which are important determinants of human capital investments, as highlighted by Cunha and Heckman (2007) and Becker et al. (2010).

I model a competitive equilibrium in which heterogeneous agents choose their occupations and years of education to maximize income, taking wage schedules as given. Likewise, a representative firm hires workers, taking the wage schedule as given. Workers of various skill levels are matched to sector types that produce services of different complexities. The market equilibrium is characterized by a mapping of skills (given by the years of education of each worker) on complexities, as in Tinbergen (1956). Because highly skilled workers are assumed to have a comparative advantage in complex services, in equilibrium, they will be allocated to complex services.

I build on Teulings (1995), Kaboski (2009), and Parro (2012b). Those authors use variants of an assignment model to study some aspects of the wage distribution [Teulings, (1995)], the forces behind schooling and wage growth [Kaboski (2009)], and the rise and fall in the US gender gap in education [Parro (2012b)]. However, none of them empirically study the fall and rise of the US college wage premium. In this paper, I build a model that shares some of the structure of those frameworks. I extend those models by including heterogeneity in the costs of accumulating human capital, by modeling "psychic or effort" costs in the investment decisions of agents [as in Becker et al. (2010)], and by allowing for the existence of polarizing demand shifts, which could be important for understanding the movement of the skill premium in the most recent decades, as highlighted by Autor et al. (2003), Goos and Manning (2007), and Acemoglu and Autor (2010), among others. I use the model to quantify the total causal effect of supply and demand forces, and the relevant nature of the demand forces moving the skill premium across different decades. To the best of my knowledge, no other paper in the literature has studied the causal effect of different demand factors on the skill premium using the rich structure built in this paper.

2.1. Production Technology

The production of the unique final good Y is performed by aggregating the output S of a continuum of sectors. Sectors are indexed by the "complexity" of the service produced, i. The production function of the final good can be expressed as

$$Y = \left(\int_{\underline{I}}^{\overline{I}} S\left(i\right)^{\frac{\sigma-1}{\sigma}} di \right)^{\frac{\sigma}{\sigma-1}}, \tag{1}$$

where σ denotes the elasticity of substitution between services in the production of the final good. $\overline{I}$ and $\underline{I}$ are the least and most complex services produced, respectively.

Before analyzing the production function of each service, I will define some concepts. h is a measure of a worker's years of education, and $A(i, h)$ is the productivity of a worker with h years of education producing a service of complexity i. Additionally, denote by $n(i, h)$ the amount of labor supplied by agents with h years of education in sector i. Total labor supply is normalized to unity; therefore, $n(i, h)$ is the density function of workers of type h producing a service of type i within the labor supply. Production of service i can be expressed as follows:

$$S\left(i\right) = \int_0^{\infty} A\left(i, h\right) n\left(i, h\right) dh. \tag{2}$$

Function $A(\cdot)$ is assumed to be twice differentiable. Additionally, I make the following three general assumptions. First, I assume that more skilled workers have an absolute advantage over less skilled workers ($\partial A\left(i, h\right) / \partial h > 0$). That is, workers with higher skills are more productive, irrespective of the job in which

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they are employed. The direct implication of this assumption is that more educated workers earn higher wages. Additionally, I assume that more complex sectors have an absolute advantage over less complex sectors, that is, $(\partial A(i,h)/\partial i > 0)$. Third, I assume that more educated workers have a comparative advantage in more complex sectors $(\partial \log A(i,h)/\partial i \partial h > 0)$. That is, the relative productivity gain from an additional unit of skill increases with the complexity of the job.[5]

In order to achieve empirical results, I have to make specific assumptions on the functional form of $A(\cdot)$. I use a convenient parameterization that meets the previous general assumptions regarding $A(\cdot)$ and, in addition, that captures the intrinsic nature of the demand forces to be quantified:

$$A(i,h) = \exp\left(i^{\delta}h + \lambda(h-12) + \chi_0 i^2 + \chi_1 i\right). \tag{3}$$

Notice that the parameterization for the function $A(\cdot)$ meets the assumptions of absolute and comparative advantages of more skilled workers. Additionally, I impose $\chi_0 = -\chi_1/2\bar{\imath}$ for $\underline{I} < \bar{\imath} < \overline{I}$. The parameter χ_1 is the source of polarizing product demand shifts and $\bar{\imath}$ is the polarizing point. When $\Delta\chi_1 < 0$, the relative demand for services around complexity $\bar{\imath}$ falls, whereas the relative demand for services produced by low- and high-skill workers rises. When $\Delta\chi_1 > 0$, the opposite polarizing product demand shift is triggered.

The representative firm producing the final good hires workers, taking the wage schedule as given. The maximization problem of the representative firm in this economy model is

$$\max_{n(i,h)} \left\{ \left(\int_{\underline{I}}^{\overline{I}} \left[\int_0^{\infty} A(i,h)\, n(i,h) dh \right]^{\frac{\sigma-1}{\sigma}} di \right)^{\frac{\sigma}{\sigma-1}} - \int_{\underline{I}}^{\overline{I}} \int_0^{\infty} w(i,h)\, n(i,h)\, dh di \right\}, \tag{4}$$

where $w(i,h)$ is the wage earned by a worker with h years of education working in sector i. The first-order condition for labor is

$$w(i,h) = A(i,h) \left(\frac{Y}{S(i)} \right)^{\frac{1}{\sigma}}. \tag{5}$$

Equation (5) characterizes the first-order condition of the representative firm.

Demand forces. Three types of demand forces are embodied in the production technology of this economy model. The first is a within-sector SBTC, denoted by the parameter λ. An increase in λ raises the productivity of workers with more than 12 years of education but decreases the productivity of workers with less than 12 years of education, within each sector. This technological improvement monotonically increases the relative wages of skilled workers by increasing the real wages of workers with 12 or more years of education but decreasing the wages of other types of workers.

The second demand force is a type of structural transformation, triggered by the parameter $\overline{I}$. A rise in $\overline{I}$ reflects the creation of new sectors that produce more complex services. Those new sectors demand more skilled workers, given that more educated workers have comparative advantages in sectors that produce more complex services. Therefore, as the complexity of the services produced by the economy rises, a reallocation of labor toward more complex services should be observed.

The third demand force is a polarizing product demand shift within the existing sectors of the economy. As explained above, this force is triggered by the parameter χ_1: $\Delta\chi_1 < 0$ ($\Delta\chi_1 > 0$) implies that the relative demand for services around complexity $\bar{\iota}$ falls (rises), whereas the relative demand for services produced by low- and high-skill workers rises (falls). If the services around complexity $\bar{\iota}$ are performed by high-school graduates, a polarizing force such that $\Delta\chi_1 < 0$ should push the skill premium up and produce a non-monotonic change across the wage structure—that is, a wage polarization in favor of low- and high-skill workers.[6]

It is important to notice that the distinguishing element among the three demand forces included in the model is the differential impact they have on different data moments of the labor market, even though they could have isomorphic effects on the skill premium and quantity of college graduates. The creation of high-skill sectors is characterized by a reallocation of workers toward high-skill sectors. An SBTC is characterized by an increase in the relative productivity of more educated workers within existing sectors. This technological change is monotonic across schooling levels. Both phenomena are skill-biased in the sense that they raise the relative demand for more educated workers. However, a distinguishing element is the fact that a structural transformation produces a strong reallocation of workers from low-skill to high-skill sectors while, in contrast, the reallocation of workers is weak when an SBTC triggers a rise in the demand for more educated workers.

Additionally, polarization comprises two related phenomena: job polarization and wage polarization. Job polarization refers to the simultaneous growth of the share of employment in high-skill, high-wage sectors and low-skill, low-wage sectors. Wage polarization refers to non-monotonic changes in earnings levels observed across the earnings distribution, even as the overall "return to skill" as measured by the college/high-school earnings gap may monotonically increase. Therefore, even though polarization could be also biased in favor of college graduates, the distinguishing characteristics of this force, compared with the others included in the analysis, are the non-monotonic changes in wages across sectors that it generates in the labor market. Autor et al. (2003) and Acemoglu and Autor (2010) find that polarization seems to be an important demand force in the US market in recent decades.

The specification chosen for the demand forces precisely captures the intrinsic nature of each of those forces. The non-isomorphic effects that each of the previously discussed demand forces have on different data moments of the labor market will be key for the identification of the parameters of the model, as will be exposed in Section 3.

2.2. Agents

The economy is populated by a continuum of agents that spend their endowment of time working and accumulating education through formal schooling. Each agent lives for just one period and has an endowment of time T. To get h years of education, agents must spend h years in school, which is an indirect cost of schooling.

In this economy model, agents are heterogeneous and are measured along a continuous one-dimensional scale. They are characterized by a single index variable denoting inherent ability. Agents' inherent abilities are distributed with a positive density across a bounded interval $\left[\underline{\alpha}, \overline{\alpha}\right]$ according to a continuously differentiable density function $f(\alpha)$, where α represents inherent ability. Inherent ability affects the cost of investing in education. Specifically, there are "psychic costs" of attending school which are decreasing in the inherent abilities of agents and proportional to the indirect cost of schooling.[7] The proportionality factor is given by a continuous, decreasing, and differentiable function $\Omega(\alpha)$.

Agents choose years of education and the sector where they work to maximize lifetime income, taking wage schedules as given. Then, the maximization problem of agents of type α is

$$\max_{i,h} \{[T - h(1 + Z + \Omega(\alpha))] w(i, h)\}, \tag{6}$$

where $T - h$ is the amount of effective working time (which is decreasing in h), $w(i, h)$ is the indirect cost of each year of schooling, and $\Omega(\alpha) hw(i, h)$ is the monetary value of the psychic costs of acquiring h years of education. In terms of data, $w(i, h)$ is the average annual wage that a full-time, full-year (FTFY) worker with human capital h earns in sector i during his lifetime.[8]

In the model, Z are the supply shifters. A rise in Z reduces the supply of college graduates and increases the skill premium (controlling for compositional effects). The modeling of the supply shifter in equation (6) contains, in a reduced form, the ideas developed by Becker et al. (2010) for the supply of college graduates. The supply shift component is intended to capture two types of elements that are important in the human capital investment decision and that go beyond foregone earnings: tuition costs and net non-monetary benefits of education. More years of schooling require an agent to pay higher tuition costs. Additionally, as discussed by Becker et al. (2010), a higher education improves several aspects of life, constituting the non-monetary benefits of schooling. There could be also non-monetary costs of a higher education that do not depend on agents' abilities (and, thus, do not enter into the psychic cost function). Thus, a fall in Z represents a supply shock in favor of more educated agents that captures a fall in tuition costs and/or a rise in net non-monetary returns to higher education. The motivation to model Zh as a multiplicative term with wages follows from the fact that (i) wages determine the monetary value of non-pecuniary benefits of education, which is relevant in a framework where agents are income maximizers, and (ii) tuition costs are proportional to the wages of more educated workers, since human capital production is intensive in human capital [Becker (1993)].

The first-order conditions of the optimization problem of agents of type α is described by the following equations:

$$[h] : \frac{1 + Z + \Omega(\alpha)}{T - h(1 + Z + \Omega(\alpha))} = \frac{\frac{\partial w(i,h)}{\partial h}}{w(i,h)}, \tag{7}$$

$$[i] : \frac{\partial w(i,h)}{\partial i} = 0, \tag{8}$$

where equation (7) is the optimal choice of education for an agent with ability α working in sector i and equation (8) is the optimal choice of sector for an agent with h years of education.

The assumptions regarding the function $A(\cdot)$ ensure that more educated workers earn higher wages in the labor market. Therefore, optimizing workers invest in education until those monetary benefits equalize all costs involved in the accumulation of human capital (direct, indirect, and psychic costs of schooling). That is, the intuition behind the first-order condition regarding h. Additionally, employers pay workers in accordance with their marginal value product. Workers will choose the sector that offers them the highest wage, since sector characteristics do not enter into any utility function (compensating differentials are ruled out from this model). That optimal decision for a worker of type α is reflected in equation (8).[9]

2.3. Equilibrium

In this section, I first define the competitive equilibrium that I am modeling, and then I analyze how the equilibrium is solved.

Competitive equilibrium. The competitive equilibrium is a set of wages $\{w(i,h)\}$, quantities $\{n(i,h)\}$, and optimal policy functions $\{i(\alpha), h(\alpha)\}$ that solve firms' and agents' maximization problems and the market clearing conditions for labor inputs.

The equilibrium allocation of workers to sectors can be described by a one-to-one correspondence between human capital and service complexities, $h(i)$, which therefore has a well-defined inverse function, $i = i(h)$. This implication follows from the assumption of perfect substitutability between types of workers within a single job type. Firms will employ workers only with the lowest cost per efficiency unit of labor. The assumption of comparative advantage guarantees that when two types of workers have an equal cost per efficiency unit of labor in one sector, they cannot have an equal cost in any other sector. Hence, when a specific type of worker is employed in a sector, there is never another type of worker employed in the same sector. Additionally, without proof, I state that $h(.)$ is differentiable in the equilibrium. Furthermore, the assumption of comparative advantage implies that $h'(i) > 0$. Highly skilled workers are allotted to complex jobs.

Solving the equilibrium. To compute the equilibrium, I solve for the inverse policy mapping of sectors to abilities $\alpha(i)$ and sectors to human capital $h(i)$. Those policy mappings are strictly increasing by the assumptions that more skilled workers have an absolute advantage over less skilled workers and that more educated workers have a comparative advantage in more complex sectors.

The labor market clearing condition requires that the demand for labor of type h working in sector i is equal to the supply. The density of workers in service type i can be derived from a change in variables $f(\alpha(i))\alpha'(i)$, where $\alpha'(i)$ is the Jacobian from transforming the density in terms of α to a density in terms of i. Therefore, the labor market clearing condition is the following:

$$n(i,h) = f(\alpha(i))\alpha'(i)(T - h(i)). \tag{9}$$

Then, for sector–education combinations that satisfy $h = h(i)$, the supply is the density of workers of type α that choose sector i. For sector–education combinations that are not optimal, the supply is simply zero.

The output of service i follows from multiplying this density by the effective time that workers spend in the workforce and the productivity of $h(i)$-type workers in service i:

$$S(i) = A(i, h(i)) f(\alpha(i))\alpha'(i)(T - h(i)). \tag{10}$$

Taking logs and differentiating equation (10) with respect to i, we have

$$\frac{S'(i)}{S(i)} = \frac{\frac{\partial A(i,h(i))}{\partial i}}{A(i,h(i))} + \frac{\frac{\partial A(i,h(i))}{\partial h}h'(i)}{A(i,h(i))} + \frac{\frac{\partial f(\alpha(i))}{\partial \alpha}\alpha'(i)}{f(\alpha(i))} + \frac{\alpha''(i)}{\alpha'(i)} - \frac{h'(i)}{T - h(i)}. \tag{11}$$

Additionally, combining the first-order condition that comes from firm optimization with the agents' optimality condition in the choice of i, we can get an expression of the constant elasticity of substitution:

$$\frac{S'(i)}{S(i)} = \sigma\left(\frac{\frac{\partial A(i,h(i))}{\partial i}}{A(i,h)}\right). \tag{12}$$

Using equations (11) and (12) produces the following second-order differential equation (SODE) that characterizes the optimal matching:

$$\frac{\alpha''(i)}{\alpha'(i)} + \left(\frac{\frac{\partial A(i,h(i))}{\partial h}}{A(i,h(i))} - \frac{1}{T - h(i)}\right)h'(i) + \frac{f'(\alpha(i))\alpha'(i)}{f(\alpha(i))} + (1-\sigma)\frac{\frac{\partial A(i,h(i))}{\partial i}}{A(i,h(i))} = 0. \tag{13}$$

Equation (13) is an SODE describing the allocation of workers of type α to sectors in market equilibrium. Appendix A describes in detail the algorithm used to solve the SODE described by equation (13).

3. CALIBRATION

In this section, I discuss the calibration strategy. Appendix B describes the data used in the calibration. The parameters of the model are the amount of effective working time $(T - h)$, the elasticity of substitution (σ), the complexity of the services produced in the economy $(\bar{I}, \underline{I})$, the location of the supply (Z), the supply shifts (ΔZ), the demand parameters $(\lambda,\ \chi_1, \bar{\imath})$, the within-sector technological change $(\Delta\lambda)$, the polarizing product demand shifts $(\Delta\chi_1)$, the rate of creation of new services $(\Delta\bar{I})$, the parameter that determines comparative advantages across sectors (δ), the distribution of inherent abilities $(f(\alpha))$, and the psychic cost function $\Omega(\alpha)$. The next sections describe in detail the calibration strategy.

3.1. Parameters Taken from Data or Previous Studies

First, as described in Appendix B, a linearization from a life-cycle model that considers schooling beginning at age 6 and retirement at age 65, an average of 11.5 years of schooling, and a discount rate of 2.5%, produces an amount of effective working time, $T - h$, equal to $39 - h$. Therefore, I use $T = 39$. Additionally, in order to calibrate the elasticity of substitution between sectors, σ, I take the parameter estimated by Katz and Murphy (1992), that is, $\sigma = 1.4$. In Section 4, I present a sensitivity analysis of the results for different values of σ.

3.2. The Psychic Cost Function

In order to calibrate the psychic cost function $\Omega(\alpha)$, I first impose a linear relationship between inherent abilities and the psychic costs paid by agents:

$$\Omega(\alpha) = E_0 + E_1\alpha. \qquad \textbf{(14)}$$

I assume a uniform distribution for α. The assumed linear functional form implies that the proportionality parameter $\Omega(\alpha)$ will also have a uniform distribution. I calibrate the psychic cost parameters (E_0 and E_1) to make the monetary value of the psychic costs paid by the agents in the model consistent with those computed by Cunha and Heckman (2007). Appendix C provides further details on the data used and the procedure followed to calibrate the psychic cost function.

3.3. Supply and Demand Location and Shifts

The remaining parameters of the model are those determining the supply and demand location $\left(Z, \bar{I}, \underline{I}, \delta, \lambda, \chi_1, \bar{\imath}\right)$ and the supply and demand shifts $\left(\Delta Z, \Delta\lambda, \Delta\chi_1, \Delta\bar{I}\right)$.

I first calibrate the model to match US data for 1970, which is the first year available in the dataset. A normalization of λ is needed in the baseline year since this parameter and the parameter $\overline{I}$ have relatively isomorphic effects on the demand for college graduates at a given moment in time. The only non-isomorphic

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effect of those parameters is on the amount of labor reallocation that they trigger to generate a given increase in schooling. Additionally, the polarizing point $\bar{\imath}$ is assumed to be a time-invariant parameter and is calibrated as the middle point of the calibrated complexities in the baseline year. This decision is grounded in the fact that this force becomes relatively isomorphic with the sectoral shifts of labor parameter, $\overline{I}$, when polarizing effects are absent. Taking the limit of the function $A(\cdot)$ when $\bar{\imath}$ tends to either $-\infty$ or $+\infty$ makes this point clear. Therefore, a time-varying polarizing point parameter would artificially undermine the relative contribution of the sectoral shifts of labor parameter, $\overline{I}$, in decades when polarizing forces do not exist. Instead, by fixing the polarizing point, we can let the data distinguish whether or not the forces moving the skill premium have polarizing characteristics.

Therefore, there are five location parameters that must be calibrated in the baseline year: Z, $\bar{I}$, $\underline{I}$, δ, χ_1. In order to calibrate those five parameters, I match five facts of the US data: the share of college-educated workers, the composition-adjusted ratio of the wages of college graduates to those of high-school graduates, the ratio of the 90th to the 50th percentile of the wage distribution, the ratio of the 50th to the 10th percentile of the wage distribution, and the average years of schooling.[10]

Additionally, the supply and demand shifts $\left(\Delta Z, \Delta\lambda, \Delta\chi_1, \Delta\bar{I}\right)$ are calibrated to match the changes in the college wage premium, changes in the share of college graduates, the change in 90th/50th ratio of wages, the change in the 50th/10th ratio of wages, and the amount of the growth in education that is explained by sectoral reallocations of labor.[11] The effects of the supply and demand parameters on those facts of the data are not linearly dependent, which allows me to identify the model. I will further discuss this point.

Table 1 shows the effect of different parameters of the model on the equilibrium values of different labor market variables.[12] The first four columns show the direction (the sign) of the effects that demand and supply forces exert on the equilibrium values of the skill premium, the share of college graduates, the 90th/50th ratio, and the 50th/10th ratio generated by the model. The last column shows the magnitude of the change in schooling that is explained by a reallocation of labor toward high-skill and more-complex sectors when different forces operate in the model. This latter moment is computed by using equation (B.1), described in Appendix B, applied to the equilibrium values generated by the model.[13]

As Table 1 exhibits, an increase in $\overline{I}$ (the creation of new and more-complex sectors effect), *ceteris paribus*, raises both the equilibrium relative quantity of college graduates and the skill premium by triggering a strong reallocation of labor toward more complex sectors. This latter element is measured by the amount of the increase in schooling that is explained by sectoral shifts of labor, compared with the amount explained by a within-sector skill upgrading. A rise in λ (the SBTC effect) produces relatively isomorphic effects on the skill premium and the share of college graduates. However, as Table 1 shows, sectoral shifts of labor are small, and it is a within-sector upgrading that is behind the increase in the

TABLE 1. Comparative static analysis

Force	Change in the parameter value	Change in equilibrium values: Skill premium	Share of college graduates	90th/50th	50th/10th	Labor reallocations (%)
SBTC (λ)	+	+	+	+	+	11%
Polarization (χ_1)	–	+	+	+	–	50%
Creation of new sectors ($\bar{I}$)	+	+	+	+	+	98%
Supply shifts (Z)	+	+	–	+	+	5%

Note: (a) Labor reallocations refers to the fraction of increase in the average years of schooling explained by sectoral shifts of labor toward high-skill and more-complex sectors; it is computed using equation (B.1). (b) Notice that the results exhibited in this table are derivatives around certain parameter values.

supply of higher education. Polarization is triggered by either a non-monotonic sector-specific technological change or a product demand shift in favor of the most and least complex sectors, as I remarked in endnote 6. Table 1 shows that the polarizing parameter, χ_1, produces a non-monotonic change in the wage structure together with a rise in the skill premium and the equilibrium share of college graduates. In other words, this parameter triggers a wage polarization in line with the nature of this type of demand force, as described in Acemoglu and Autor (2010). In Table 1, wage polarization is measured by the rise in the 90th/50th wage ratio jointly with a flattening of the 50th/10th wage ratio.

The previous discussion explains why the chosen target data moments to be matched allow the identification of the parameters of the model. First, as Table 1 shows, all demand forces, independent of their nature, produce an increase in both the college wage premium and the share of college graduates. In contrast, a supply shift raises the share of college graduates, which induces a fall in the skill premium. Therefore, by looking at the correlations between changes in price and quantity, the effect of supply and demand forces (as a whole) can be identified. In decades, when a negative correlation between the skill premium and the share of college graduates is observed, the model favors supply over demand forces.

Additionally, as exhibited in Table 1, even though all demand forces produce relatively isomorphic effects on the skill premium and the share of college graduates, their effects are non-isomorphic on other moments of the labor market. In order to disentangle the relative contributions of the creation of new high-skill sectors and a within-sector SBTC, I exploit the fact that sectoral shifts of labor toward high-skill and more-complex sectors are strong when the creation of new sectors is the driving force behind the demand shifts for higher education but close to null if a within-sector SBTC is the main force.[14] Therefore, by matching the fraction of the growth in years of education that is explained by labor reallocations, I can assess whether the creation of new sectors or the within-sector SBTC is driving the rise in the skill premium and the share of college graduates. In decades, when growth in schooling is driven more heavily by labor reallocations, the model will favor the creation of new high-skill sectors over the within-sector SBTC.

In addition, notice that both parameters $\overline{I}$ and λ produce changes that are monotonic across the complexity distribution (and, in equilibrium, the skill distribution). On the other hand, the polarizing force produces a non-monotonic change in wages across sectors. As observed in Table 1, this force tends to flatten the 50th/10th wage ratio even though it keeps pushing up the skill premium and the wage ratios in the top of the distribution. Therefore, by looking at the changes in the ratios of wages between the 90th and the 50th and the 50th and the 10th percentiles (especially the latter ratio), I can distinguish between demand forces that produce a monotonic increase in wages across the skill distribution and those that produce polarizing changes. The model favors the polarizing force in periods when a pronounced rise in the skill premium comes together with a flattening in the growth of wages in the lower tail of the distribution.

Table 2 shows how the model fits the data to be matched. We observe that, even though four parameters are used to match five data moments, the model is able to closely replicate the chosen data from the US economy.

4. RESULTS AND COUNTERFACTUALS

I present in Table 3 the calibration for the time-invariant parameters and in Table 4 the one for the time-varying parameters. On the demand side, we observe that the parameter $\bar{I}$ remains roughly constant during the pre-1980 period but rises sharply across the post-1980 period. Additionally, we observe a continual increase in the parameter λ during the post-1980 period, reflecting an SBTC pushing up the relative wages of more educated workers. Finally, we observe a continual fall of the parameter χ_1 over the post-1980 period, reflecting a polarization of wages in the labor market in favor of low- and high-skill workers. On the supply side, we observe a positive supply shift during the decade 1970–1980 followed by negative shifts during the post-1980 decades. This movement of the supply is consistent with the fall in the college wage premium during the 1970–1980 decade, followed by the rise in the skill premium in the decades that follow.

Next, I perform some counterfactual exercises to estimate the causal effect of each supply and demand force on the US skill premium. I first compute what the skill premium would have been if only an SBTC had been present. Then, I perform the same exercise considering the SBTC and the polarizing effects. After that I add the effect of a structural transformation and, finally, the supply shifts. When all forces are present, the model predicts the college wage premium observed in Table 2.[15] Using that information, I compute the marginal explanatory power of

TABLE 2. Model fit

	Data				
	1970	1980	1990	2000	2008
Skill premium	1.56	1.5	1.71	1.88	1.97
Share of college graduates	0.33	0.43	0.49	0.55	0.59
90th/50th	1.84	1.93	2.01	2.2	2.28
50th/10th	1.99	2.02	2.19	2.14	2.2
Labor reallocations	–	0.14	0.14	0.22	0.3
Average years of schooling	11.51	12.41	13.03	13.31	13.48
	Model				
	1970	1980	1990	2000	2008
Skill premium	1.54	1.49	1.69	1.86	1.99
Share of college graduates	0.31	0.42	0.47	0.52	0.56
90th/50th	1.85	1.9	1.97	2.23	2.31
50th/10th	1.99	1.99	2.18	2.13	2.21
Labor reallocations	–	0.14	0.16	0.25	0.33
Average years of schooling	11.5	12.53	12.89	13.47	13.55

Note: (a) Labor reallocations refers to the fraction of increase in the average years of schooling explained by sectoral shifts of labor toward high-skill and more-complex sectors. It is computed using equation (B.1). (b) The average years of schooling data was used as target moment to calibrate the model in the baseline year and to evaluate the model fit in an additional dimension in the other decades included in the analysis.

TABLE 3. Constant parameters

E_0	0.095
E_1	−0.014
$\overline{\alpha}$	10.33
$\underline{\alpha}$	1.43
$\widehat{T}$	39
$\underline{I}$	0.0376
δ	0.9997
$\bar{\imath}$	0.1188
σ	1.4

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TABLE 4. Time-varying parameters

	1970	1980	1990	2000	2008
λ	0	0.0013	0.021	0.0314	0.0391
χ_1	−1.3426	−4.7012	−5.9709	−21.8471	−32.9886
$\overline{I}$	0.2001	0.2013	0.2059	0.2079	0.2134
Z	0.7335	0.6531	0.7151	0.7645	0.7826

TABLE 5. Explanatory power of supply and demand forces for the skill premium (%)

	1970–1980	1980–1990	1990–2000	2000–2008	Avg.
SBTC (λ)	−8.4	59.7	19.8	14.1	21.3
Polarization (χ_1)	−7.6	2.1	36.2	27.4	14.5
Creation of new sectors ($\overline{I}$)	−3.4	7.4	9.4	35.3	12.2
Supply shifts (Z)	119.4	30.8	34.7	23.2	52.1

the supply and demand forces for the skill premium. This type of counterfactual analysis for the college wage premium is relevant and informative for two reasons: (i) the skill premium is a data moment that has experienced a striking movement over the entire period of analysis, and (ii) a counterfactual analysis is indeed needed to disentangle the relative contributions of the demand forces that exert an isomorphic effect on the college wage premium. The same conclusion cannot be reached for other moments, which explains why I have not presented a similar decomposition for the other moments.[16] The results are reported in Table 5.

We observe in Table 5 that, on average, 48% of the change in the US skill premium during the last four decades is explained by demand factors. Supply forces explain the remaining 52% of the skill premium variation. However, the relative contribution of each supply and demand force varies across decades. We observe that positive supply shifts completely explain the fall of the skill premium during the period 1970–1980.[17] On the other hand, demand forces play a major role in the post-1980 period, when the skill premium rises.

Among the demand forces, we observe an increasing contribution of polarizing product demand shifts to the rise of the skill premium during the post-1980 period. The results show that those polarizing product demand shifts reduced the relative demand for middle-complexity services, which are mostly performed by high-school graduates, across the post-1980 decades. During the post-1980 period, the contribution of this force to the rise in the college wage premium goes from 2% in the period 1980–1990 to 36% in 1990–2000 and 27% in the last decade included

TABLE 6. Average explanatory power of supply and demand forces (%) and σ

	$\sigma = 1.4$	$\sigma = 1.7$	$\sigma = 2$
Demand	47.9	53.6	61.1
Supply	52.1	46.4	38.9

Note: σ is the elasticity of substitution between services in the production of the final good.

in the analysis. On the other hand, the within-sector non-neutral technological change exhibits a decreasing contribution over those decades. The contribution of this demand force declines from 60% to 14% over that period. On average, 31% of the demand-driven rise in the skill premium during the post-1980 period is explained by polarizing product demand shifts within existing sectors, 44% by an SBTC, and 25% by the creation of new high-skill sectors.

I perform some additional exercises to evaluate the sensitivity of the results to different parameter values and how consistent they are with what the economic theory predicts. I recalibrate the model considering different values for the elasticity of substitution σ and the distribution of abilities $f(\alpha)$. I study whether the estimated changes in the contribution of supply and demand forces for different elasticities are in line with what economic theory predicts.

Some evidence on the elasticity of substitution has been provided by Katz and Murphy (1992), Murphy and Welch (1992), Fernandez (2000), and Acemoglu and Autor (2010). In general, that literature supports an elasticity of substitution of around 1.4–2.0. I choose the middle and the upper bound of that range for my sensitivity analysis. Table 6 shows the average contribution of supply and demand forces considering different values for the elasticity of substitution. We observe that the average contribution of the demand forces to the skill premium increases as σ rises. This result is in line with what economic theory predicts. Bigger demand shifts are needed to explain a given change in quantities and prices when demand becomes more elastic. We observe that the contribution of demand forces increases from 48% to 61% as σ rises from the baseline value to 2.

Next, I perform a second sensitivity analysis regarding the supply elasticity. In the baseline calibration, I first calibrate men's distribution of abilities by using the evidence provided by Cunha and Heckman (2007) on the mean monetary value of the ability cost of attending college for a sample of white males from the NLSY 1979. Then, I pick from the literature a proxy for the gender ratio of the mean and variance of abilities to calibrate women's abilities. I use the mean and variance of the high-school rank (percentiles) reported by Goldin et al. (2006). Finally, with those pieces of information, I calibrate the distribution of abilities for the total sample and, thus, the supply elasticity (see Appendix C for further details).

TABLE 7. Alternative proxies for $\widetilde{\sigma}_{\alpha}$

8th grade composite ability	1.02
Hours homework/wk in 8th grade	1.03
High-school grades	1.06
12th grade composite ability	1.07
Class rank (percentile)	1.08
Middle school grades	1.11
Behavior problem	1.54
Hours of homework/wk in 12th grade	1.72
Behavior composite	2.08

Source: Jacob (2002).
Note: $\widetilde{\sigma}_{\alpha}$ is the ratio between the variance of men's abilities and the variance of women's abilities.

TABLE 8. Average explanatory power of supply and demand forces (%) and $\widetilde{\sigma}_{\alpha}$

	$\widetilde{\sigma}_{\alpha} = 1.07$	$\widetilde{\sigma}_{\alpha} = 2.08$
Demand	47.9	38.7
Supply	52.1	61.3

Note: $\widetilde{\sigma}_{\alpha}$ is the ratio between the variance of men's abilities and the variance of women's abilities.

However, other proxies for abilities have been reported in the literature. Table 7 presents those alternative proxies.

Denote by $\widetilde{\sigma}_{\alpha}$ the ratio between the variance of men's abilities and the variance of women's abilities. We observe in Table 7 that the proxies for the ratio $\widetilde{\sigma}_{\alpha}$ range from 1.02 to 2.08. In this sense, the proxy used in the baseline calibration constitutes a relatively conservative number ($\widetilde{\sigma}_{\alpha} = 1.07$ in the baseline scenario). Therefore, as a final sensitivity analysis, I calibrate the model using as a proxy for $\widetilde{\sigma}_{\alpha}$ the highest value in Table 7. Considering the highest value for $\widetilde{\sigma}_{\alpha}$, I get $\bar{\alpha} = 9.90$ and $\underline{\alpha} = 1.86$, which implies a fall in the variance of the psychic costs by 18.4%. Table 8 shows the results using the new calibrated values for the ability distribution.

We observe that as the variance of abilities decreases, the relative contribution of supply forces rises. A lower variance of abilities implies that agents are more homogeneous and, thus, the elasticity of the supply of more educated workers is greater. With a more elastic supply curve, greater negative supply shifts are needed to explain the rise in the college wage premium in the context of an increasing demand for college graduates during the post-1980 period. Analogously, bigger positive supply shifts are needed to explain the fall in the college wage premium in the context of a stable demand for college graduates during the pre-1980 period. The average contribution of supply forces increases from 52% to 61%.

Therefore, the sensitivity analysis shows that with a higher elasticity of substitution the role of demand forces is amplified. On the other hand, with a lower variance of abilities the effects of supply forces become more relevant. Those results are consistent with what economic theory predicts.

5. CONCLUSIONS

In this paper, I build an assignment model to delve into the nature of the demand forces moving the demand for education and the skill premium across decades. The model distinguishes between skills and sectors and allows me to look at different data moments of the labor market on which different type of forces have non-isomorphic effects. Several forces were put in competition in a unified framework: (i) a within-sector non-neutral technological change, (ii) the creation of new high-skill services/sectors, (iii) polarizing product demand shifts, and (iv) shifts in the relative supply of skilled labor. The model was calibrated to match data moments of the US economy. The results show that positive supply shifts almost completely explain the fall of the skill premium during the period 1970–1980, whereas demand forces play a more relevant role during the post-1980 period. Among the demand forces, the results show an increasing contribution of polarizing product demand shifts over the decades.

This paper contributes to the understanding of the nature of the demand forces pushing up the demand for education. I have shown that putting several demand forces into competition in the same model reveals that the relevant nature of the demand-side channels behind the skill premium movements is not unique but varies across decades. This conclusion contrasts with the one derived from a canonical model where a unique nature is attributed to the demand forces pushing the skill premium up. This paper shows that the intrinsic nature of the forces producing shocks in the labor market is a key determinant of the impact they have on the skill premium.

In future research, the model can be extended by including other demand forces that are candidate explanations for movements in the skill premium not only in the US economy but also in developing countries—for instance, international trade and some complementarity between imports of capital goods and skilled workers. A second interesting avenue for future research consists in enriching the supply side of the model in such a way that the rich decomposition exhibited in Table 5 for the demand forces can be performed for supply forces of different natures. Additionally, the analysis carried out in this paper shows how we can build decompositions for other relevant moments of the labor markets using a theoretical calibration-based approach. To do so, we would first need to identify in the literature some candidate forces triggering the phenomenon to be studied. Then, we should motivate the existence of (i) an isomorphic impact that those forces have on the target phenomenon but (ii) non-isomorphic effects on other moments. Next, we would need to place the target phenomenon in a framework that allows us (i) to include several candidate forces in the same framework and (ii) to look at data moments on which those forces exert non-isomorphic effects, even though they trigger an isomorphic effect on the target phenomenon. After that, we could carry out an analogous (but not identical) analysis to the one I perform in Tables 1–5 of this paper in order to get a decomposition of the relevant nature behind the forces impacting the target phenomenon. The framework and analysis developed in this paper constitutes a stepping stone for the analysis of all those issues.

NOTES

1. See, e.g. Bound and Johnson, (1992), Katz and Murphy (1992), Murphy and Welch (1992), and Juhn, Murphy, and Pierce (1993).

2. See Katz and Murphy (1992).

3. See Doms et al. (1997), Dunne et al. (1997), Autor et al. (1998), Autor and Katz (1999), Autor et al. (2003), Levy and Murnane (2004), Bartel et al. (2007), among others.

4. For instance, Heckman et al. (1998) develop and estimate an overlapping generation model with heterogeneous skills, endogenous schooling choice, and post-school on-the-job investment to study the college wage premium and skill formation. On the demand side, they only approximate a skill-biased technological change by a trend estimated from an aggregate technology and, thus, they do not disentangle the relative quantitative contributions of different types of demand forces. He and Liu (2008) build a model in which an observed measure of technological change can replicate the observed changes in wage inequality and skill accumulation. He (2012) extends He and Liu (2008) by presenting a richer modeling of the college choices. However, an exploration of the relative quantitative importance of different demand forces is missing in He and Liu (2008) and He (2012). Jones and Yang (2016) focus their analysis on understanding the forces behind the rise in college costs between 1961 and 2009. The authors do not estimate the quantitative importance of different demand forces for the skill premium either.

5. Those assumptions imply that $A(\cdot)$ is not only strictly logsupermodular but also strictly supermodular.

6. Notice that we can alternatively interpret this polarizing effect as a sector-specific technological change that increases the productivity of any worker producing in the sector benefited by the technological improvement.

7. The assumption of proportionality between the monetary value of the psychic costs and the indirect cost of schooling is motivated by the analysis by Becker et al. (2010) and Cunha and Heckman (2007). Those authors point to two pieces of evidence: first, the fact that getting more years of education not only requires agents to spend more years in school but also incurs greater psychic (ability or effort) costs, and second, the fact that abler individuals have lower non-monetary costs of schooling. Those elements are captured by a multiplicative term $h\Omega(\alpha)$, with $\Omega'(\alpha) < 0$. A third piece of evidence is the quantification, in monetary terms, that Cunha and Heckman (2007) provide for the psychic costs of

schooling. I use that evidence to take the modeling of the psychic costs to the data. To do so, I need to assume a multiplicativity between the elements determining the psychic costs of schooling and wages. As explained in Section 3, that multiplicativity together with the assumption of a uniform distribution of abilities allows me to calibrate the psychic cost function $\Omega(\alpha)$.

8. The model transforms a life-cycle problem into a one-period problem, which yields a simple solution. Solving a dynamic model would require strong assumptions on the future path of exogenous variables, which does not necessarily reflect the most empirically relevant form of student belief formation. Dillon (2016) studies how students build expectations of the future price of college skills when making college enrollment decisions. She compares two models of student belief formation, static expectations, and perfect foresight, and tests which assumption better fits observed patterns of college enrollment. She finds that the static expectations assumption fits observed patterns of college enrollment between 1970 and 1995 far better than the perfect foresight model. The author concludes that students deciding whether to enroll in college appear to rely mostly on the earnings of current workers when forecasting their own expected gains from a college degree. Therefore, the evidence provided by Dillon (2016) supports the idea that agents may indeed choose their schooling based almost solely on current returns, since changes in returns may be difficult to forecast.

9. We can verify in the calibrated model that, in equilibrium, $w(i, h)$ is continuous and strictly concave in both i and h. Therefore, the objective is strictly concave in i and the first-order condition for the optimal choice of i is satisfied with equality. Second, in the calibrated model, all types of agents chose a level of education $h > 0$. Therefore, the first-order condition for the optimal choice of human capital is also satisfied with equality.

10. Notice that if we just want to set the position of the demand for college graduates at one moment in time, in principle, χ_1 is isomorphic with other demand parameters, and thus this parameter could have also been normalized in the baseline year. However, if we want to have a more complete characterization of the wage structure in the baseline year, we need to calibrate χ_1. This is because of the polarizing effect exerted by this parameter on the wage structure. In both cases, with the location of the demand calibrated, the decade-by-decade contribution of the polarizing force can be quantified by matching the data moments described below. Following the suggestion of an anonymous referee, I pursued the second route.

11. Appendix B shows how the latter variable is built.

12. Notice that the target moments exhibited in Table 1 involve the wage distribution, the supply of skills, and the amount of schooling growth, explained by reallocations of labor toward more complex sectors. Those target moments are computed by using as inputs the numerical solution of the optimal policy function $i(\alpha)$, equation (A.5) (to compute the optimal policy function $h(\alpha)$), equation (5) (to compute the wage distribution), and equation (B.1) described in Appendix B.

13. In the model, sectors are elements of the production process that use different production technologies and whose elasticity of substitution in the production of the final good is given by the parameter σ. The empirical proxy for the a model sector is the corresponding industry data. I compute the labor reallocations generated in the model by first dividing into evenly spaced points the continuous of model sectors calibrated for the baseline year. Then, I compute the labor share and the average years of education in each of those model sectors. Finally, I use equation (B.1) to compute the fraction of the change in schooling (average years of schooling) that is explained by reallocations of labor toward high-skill and more-complex sectors. The comparative statics for this model moment are exhibited in the last column of Table 1.

14. The comparative statics exhibited in Table 1 support this statement. We observe that an increase in λ (SBTC) generates a rise in the equilibrium value of the skill premium, the share of college graduates, the 90th/50th ratio, and the 50th/10th ratio. However, only 11% of the equilibrium change in schooling (average years of schooling) is explained by reallocations of labor toward high-skill and more-complex sectors. On the other hand, even though a rise in $\overline{I}$ (creation of new sectors) produces a change in the same direction (isomorphic) in the model moments of the first four columns of Table 1, the equilibrium change in schooling that is explained by reallocations of labor toward high-skill and more-complex sectors is 98% when this force operates.

15. The order in which the forces are introduced does not significantly alter the magnitude of the effects.

16. First, the other moments included as targets for the calibration present a significant variation only in specific decades (for instance, earnings polarization), which limits any relevant analysis to specific periods only. Second, the calibration strategy is precisely based on the fact that the effect exerted by the demand forces included in Table 5 on the other moments of Table 1 (different from the skill premium) is nonisomorphic. That noninsomorphic effect of the demand forces on those other moments implies, in turn, that we already know which of the demand forces is the one moving each of those moments. This fact converts those other moments into instruments to achieve the identification of the model.

17. The strong relative contribution of supply forces to the fall in the skill premium during the period 1970–1980 is consistent with the discussion provided by a strand of the literature arguing that the baby boom and the Vietnam War draft deferments were important shocks pushing the supply of college labor up in the early-to-mid 1970s [for instance, see Murphy and Welch (2001) and Card and Lemieux (2001b)].

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APPENDIX A: SOLUTION OF THE SODE

The actual SODE solved is not (13), but its equivalent in terms of the inverse $i\left(\alpha\right)$. Using the chain rule, I first substitute $h'\left(i\right) = h'\left(\alpha\right)\alpha'\left(i\right)$ in (13). Additionally, using the inverse rule for derivatives, we have that $\alpha'\left(i\right) = \frac{1}{i'(\alpha)}$ and $\frac{\alpha''(i)}{\alpha'(i)} = -\frac{i''(\alpha)}{\left[i'(\alpha)\right]^2}$. Given the uniform distribution for α, we have that $\frac{f'(\alpha(i))}{f(\alpha(i))} = 0$. Therefore, I can express the SODE in terms of abilities:

$$i''\left(\alpha\right) = \left(\frac{\frac{\partial A(i(\alpha),h(\alpha))}{\partial h}}{A\left(i\left(\alpha\right),h\left(\alpha\right)\right)} - \frac{1}{T-h\left(\alpha\right)}\right)h'\left(\alpha\right)i'\left(\alpha\right)+\left(1-\sigma\right)\frac{\frac{\partial A(i(\alpha),h(\alpha))}{\partial i}}{A\left(i\left(\alpha\right),h\left(\alpha\right)\right)}\left[i'\left(\alpha\right)\right]^2, \tag{A.1}$$

where

$$\frac{\frac{\partial A(i,h(i))}{\partial h(i)}}{A\left(i,h\left(i\right)\right)} = i\left(\alpha\right)^{\delta} + \lambda, \tag{A.2}$$

$$\frac{\frac{\partial A(i,h(i))}{\partial i}}{A\left(i,h\left(i\right)\right)} = \delta i\left(\alpha\right)^{\delta-1}h\left(\alpha\right) + 2\chi_0 i\left(\alpha\right) + \chi_1. \tag{A.3}$$

The remaining step is to find an expression for $h\left(\alpha\right)$ and $h'\left(\alpha\right)$. From the optimality condition for the representative firm, I get

$$\frac{\frac{\partial w(i,h)}{\partial h}}{w\left(i,h\right)} = \frac{\frac{\partial A(i,h(i))}{\partial h(i)}}{A\left(i,h\left(i\right)\right)} = i\left(\alpha\right)^{\delta} + \lambda. \tag{A.4}$$

Then, using the optimality condition for h, we have

$$h\left(\alpha\right) = \frac{T}{1+Z+\Omega\left(\alpha\right)} - \frac{1}{i\left(\alpha\right)^{\delta}+\lambda}, \tag{A.5}$$

$$h'\left(\alpha\right) = \frac{\delta i\left(\alpha\right)^{\delta-1}i'\left(\alpha\right)}{\left(i\left(\alpha\right)^{\delta}+\lambda\right)^2} - \frac{T\Omega'\left(\alpha\right)}{\left(1+Z+\Omega\left(\alpha\right)\right)^2}. \tag{A.6}$$

To solve the SODE, I discretize the ability space and use a shooting algorithm to solve for the boundary conditions ($i(\underline{\alpha}) = \underline{I}$; $i(\overline{\alpha}) = \overline{I}$).

APPENDIX B: DATA CONSTRUCTION

Earnings and relative supply of college graduates. The data used to build earnings and the share of college graduates were taken from Acemoglu and Autor (2010). The authors extract the data on earnings from the March CPS dataset for the years 1963–2008. The skill premium is measured by the composition-adjusted college/high-school log weekly wage ratio. I compute in the model the composition-adjusted college wage premium by dividing the college and high-school categories into four relevant groups (high-school graduate, some college, college graduate, and greater than college) and taking the weighted average wage of the relevant composition-adjusted cells using a fixed set of weights equal to the average employment share of each group. This procedure is similar to the one followed by Acemoglu and Autor (2010) to generate the composition-adjusted college wage premium, used as one of the target facts in my calibration. Additionally, from the earnings data available in Acemoglu and Autor (2010), I compute the 90th/50th and the 50th/10th wage ratios using a three-year moving average of the 10th, the median and the 90th percentiles of weekly wages calculated for FTFY workers, excluding the self-employed and those employed in military occupations. Finally, Acemoglu and Autor (2010) build the share of college graduates by considering all persons aged 16–64 who reported having worked at least one week in the earnings years, excluding those in the military. I use the share of college graduates as a measure because it is frequently used in the literature on the skill premium to proxy for the relative supply of college graduates (see Acemoglu and Autor 2010 for further details).

Labor reallocations. The data to build the fraction of the growth in schooling that is explained by labor reallocations were extracted from decennial censuses for the years 1970, 1980, 1990, and 2000, and from the American Community Survey for the year 2008. I use the following decomposition:

$$\overline{H}_{t+1} - \overline{H}_t \approx \sum_{i=1}^{\overline{I}} \left(\frac{\overline{h}_{i,t+1} + \overline{h}_{i,t}}{2} \right) (l_{i,t+1} - l_{i,t}) + \sum_{i=1}^{\overline{I}} \left(\frac{l_{i,t+1} + l_{i,t}}{2} \right) (\overline{h}_{i,t+1} - \overline{h}_{i,t}), \quad \text{(B.1)}$$

where $\overline{H}_t$ denotes the average years of schooling at year t, $\overline{h}_{i,t+1}$ denotes the sectoral average years of schooling, and $l_{i,t}$ is the share of labor allocated to sector i. The first term of the right-hand side of equation (B.1) corresponds to the changes in education due to sectoral shifts of labor, whereas the second term represents the changes due to a within-sector skill upgrading. In the decomposition described by equation (B.1), I used the 133

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sectors included in the 2000 decennial census, and only FTFY workers age 22–64 years were included.

Monetary value of psychic costs. The data were taken from Cunha and Heckman (2007). Further details are provided in Appendix C.

Lifetime earnings. I follow Kaboski (2009) to produce a lifetime earnings approximation. Specifically, the approximation for the amount of effective working time and, thus, for lifetime earnings is built as follows. We can define discounted lifetime earnings as

$$V(h) = \int_h^{\widehat{T}} e^{-d(t-\overline{H})} w(h) dt = w(h) \left(\frac{e^{-d(\widehat{T}-\overline{H})} - e^{-d(h-\overline{H})}}{-d} \right), \qquad \text{(B.2)}$$

where d is a discount containing the interest rate net of wage growth and a linear return to experience. $\overline{H}$ is the average years of schooling, which is used as a reference point for discounting because it is the margin between more schooling and entering the labor market for the average student. Solving (B.2) and using a first-order Taylor approximation around $\overline{H}$ for the amount of effective working time, $\frac{e^{-d(\widehat{T}-\overline{H})} - e^{-d(h-\overline{H})}}{-d}$, we get

$$V(h) \approx \left(\frac{e^{-d(\widehat{T}-\overline{H})} - 1}{-d} + \overline{H} - h \right) w(h). \qquad \text{(B.3)}$$

Therefore, I use $T - h$ as the amount of effective working time, where $T = \frac{e^{-d(\widehat{T}-\overline{H})} - 1}{-d} + \overline{H}$. In order to calibrate T, I use $\widehat{T} = 59$ (age of retirement—5), an average of 11.5 years of schooling, and d is calibrated as the average interest rate minus the growth in wages across all ages, and minus an estimated return to experience from a Mincerian specification ($d = 2.5\%$). Doing so, I get $T = 39$. The formulation given by equation (B.1) reflects a static expectations measure of the discounted lifetime earnings. Therefore, it yields a local elasticity of schooling decisions to relative wages more consistent with a life-cycle model but still within a static expectations framework [like the one empirically supported by Dillon (2016)].

APPENDIX C: CALIBRATION OF THE PSYCHIC COST FUNCTION

Denote by $PV_c(h_c)$ the mean monetary value of the ability cost (in year 2000 dollars) of attending college for college graduates, by $PV_{hs}(h_c)$ the mean monetary value of the ability cost (in year 2000 dollars) of attending college for high-school graduates, by $w_c(h_c)$ the average annual wage that a college graduate earns during his lifetime, by $w_{hs}(h_c)$ the average annual wage that a high-school graduate would earn during his lifetime if he had chosen to be a college graduate, h_c the average years of schooling of a college graduate in 2000, by α_c the mean inherent ability of agents with $h \geq 16$ (college graduates), and by α_{hs} the mean inherent ability of agents with $12 \leq h < 16$ (high-school graduates). Following this notation, we have that the indirect costs of going to college for the typical college and high-school graduates are $h_c w_c(h_c)$ and $h_c w_{hs}(h_c)$, respectively. Therefore, given that I have assumed that the monetary value of the psychic costs of going to college is proportional to the indirect costs, with data on the $PV_c(h_c)$, $PV_{hs}(h_c)$, h_c, $w_c(h_c)$, and $w_{hs}(h_c)$, I compute

$$\Omega(\alpha_c) = \frac{PV_c(h_c)}{h_c w_c(h_c)}, \tag{C.1}$$

$$\Omega(\alpha_{hs}) = \frac{PV_{hs}(h_c)}{h_c w_{hs}(h_c)}. \tag{C.2}$$

Equations (C.1) and (C.2) show the proportionality factor $\Omega(\cdot)$ for the typical college and high-school graduates, respectively.

To compute the upper and lower limits of that distribution of the psychic costs ($\Omega(\underline{\alpha})$ and $\Omega(\bar{\alpha})$, respectively), I use the properties of a uniform distribution and data on the fraction of the population with a college education. Denote by p_c the fraction of the population with a college education. $\Omega(\underline{\alpha})$ is the psychic cost parameter of the least able agent (who has the highest cost) and $\Omega(\bar{\alpha})$ is the psychic cost parameter of the most able agent (who has the lowest cost). Therefore, if the fraction of agents with a college education is p_c and the distribution of Ω is uniform, it must be true that the psychic cost parameter for the least able college graduate is $\left(\Omega(\underline{\alpha}) - \Omega(\bar{\alpha})\right) p_c + \Omega(\bar{\alpha})$. The psychic cost parameter for the most able college graduate is $\Omega(\bar{\alpha})$. Therefore, the psychic cost parameter for the typical college graduate (the one with the mean abilities among college graduates) is given by

$$\Omega(\alpha_c) = \frac{\left(\Omega(\underline{\alpha}) - \Omega(\bar{\alpha})\right) p_c + 2\Omega(\bar{\alpha})}{2}. \tag{C.3}$$

Additionally, denote by p_{hs} the fraction of the population with a completed high-school education (but who have not earned a college degree). Then the psychic cost parameter for the least able high-school graduate is $\left(\Omega(\underline{\alpha}) - \Omega(\bar{\alpha})\right)(p_c + p_{hs}) + \Omega(\bar{\alpha})$. The psychic cost parameter for the most able high-school graduate is $\left(\Omega(\underline{\alpha}) - \Omega(\bar{\alpha})\right) p_c + \Omega(\bar{\alpha})$. Therefore, the psychic cost parameter for the typical high-school graduate is given by

$$\Omega(\alpha_{hs}) = \frac{\left(\Omega(\underline{\alpha}) - \Omega(\bar{\alpha})\right)(2p_c + p_{hs}) + 2\Omega(\bar{\alpha})}{2}. \tag{C.4}$$

Then, equations (C.3) and (C.4) constitute a system of two equations and two unknown variables ($\Omega(\underline{\alpha})$ and $\Omega(\bar{\alpha})$). Therefore, using (C.3) and (C.4), I get the limits of the uniform distribution for the psychic cost function. Notice that those boundaries are independent of the boundaries of the ability distribution. Therefore, we can normalize men's abilities: $U_m \sim [1; 10]$.

Finally, by imposing the condition that the least able agent in the distribution pays the highest cost and the most able agent pays the lowest cost, I get the paremeters E_0 and E_1 of equation (14):

$$\Omega\left(\underline{\alpha}\right) = E_0 + E_1\underline{\alpha}, \tag{C.5}$$

$$\Omega\left(\bar{\alpha}\right) = E_0 + E_1\bar{\alpha}. \tag{C.6}$$

Notice that (C.5) and (C.6) constitute a system of two equations and two unknowns.

Parameter Values

Using a sample of white males from the National Longitudinal Survey of Youth 1979 (NLSY79), Cunha and Heckman (2007) estimate that the mean monetary value of the ability cost (in year 2000 dollars) of attending college is $-\$14,892$ for college graduates $PV_c\left(h_c\right)$ and $\$12,715$ for high-school graduates $PV_{hs}\left(h_c\right)$. Additionally, Cunha and Heckman (2007) estimate that the present value of earnings of a typical college graduate is $\$1,390,321$ (in year 2000 dollars). The typical high-school graduate would earn $\$1,125,785$ if he had chosen to be a college graduate. The average number of years of schooling of a college graduate is 16.9 in 2000. Therefore, I get $w_c\left(h_c\right) = 1,390,321/(59 - 16.9) = 33,024$ and $w_{hs}\left(h_c\right) = 1,125,785/(59 - 16.9) = 26,741$. Additionally, from census data, I get $p_c = 0.25$ and $p_{hs} = 0.64$. Using those inputs, and equations (C.3) and (C.4), I get $\Omega\left(\underline{\alpha}\right) = 0.081$ and $\Omega\left(\bar{\alpha}\right) = -0.043$. Using equations (C.5) and (C.6), I get $E_1 = -0.014$ and $E_0 = 0.095$.

In order to calibrate the ability distribution for the total sample, I need to calibrate women's abilities. I assume that gender differences in psychic costs are only explained by gender differences in non-cognitive abilities. Therefore, the parameters E_0 and E_1 are not gender specific. Then, I pick from the literature a proxy for the gender ratio of the mean and variance of abilities. I use the mean and variance of the high-school rank (percentiles) reported by Goldin et al. (2006). It is not itself a measure of abilities. However, it is highly correlated with a bundle of abilities. Goldin et al. (2006) present the high-school rank percentiles by sex from the National Education Longitudinal Survey for the high-school graduating class of 1992. The mean high-school ranks for men and women are 5.01 and 6.00, respectively. The variances are 8.28 and 7.74 for men and women, respectively. Using this information, I get $U_f \sim [2.24, 10.94]$, where f denotes "female." Finally, to calibrate the ability distribution for the total sample, I weight the female and male distributions of abilities using the average labor force participation of each group during the whole period. I get $U_t \sim [1.43, 10.33]$, where t denotes "total."