Immiserizing Automation[*]

Vladimir Asriyan[†] Hugo Reichardt[‡] Sandro Shelegia[§]

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Abstract

Early-career jobs often serve as stepping stones to more productive occupations later in life. Automating such jobs may disrupt skill accumulation. We study this possibility in an overlapping-generations economy with career ladders. Our main result is that automation of junior tasks can be immiserizing: when its cost savings are small, automation lowers long-run output. Immiseration occurs because junior automation shifts earnings to later in life. This shift lowers the present value of experience-intensive careers, so that fewer workers pursue them, and the supply of experienced workers falls. As the transition to the new steady state is Pareto efficient, any policy that averts immiseration hurts at least some workers. Incumbent experienced workers, for instance, benefit from higher senior wages without having suffered lower wages as juniors. In the context of U.S. robot automation, we provide empirical support for the theory's key predictions and explore its aggregate implications.

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[†]CREi, ICREA, BSE, and CEPR. vasriyan@crei.cat.

[‡]CREi, BSE, and CEPR. hreichardt@crei.cat.

[§]UPF, BSE, and CEPR. sandro.shelegia@upf.edu.

1 Introduction

Work performed early in one's career is valuable not only for what it produces, but also for what it teaches. By carrying out junior tasks, workers accumulate the experience required to perform more demanding, better-paid tasks later in their careers. Automation of junior tasks may thus disrupt workers' skill accumulation. In this paper, we study the implications of such technological disruption for the long-run output of the economy.

We consider an overlapping-generations economy in which workers face one key trade-off: whether to earn higher wages when young or to accumulate experience and earn higher wages later in life. Specifically, they can supply labor to either of two sectors. In the "modern" sector, workers progress along a career ladder: performing senior tasks requires prior experience in junior tasks. In the "traditional" sector, no experience is required. Workers sort into sectors based on comparative advantage and smooth consumption through financial markets. To isolate the key theoretical mechanisms, we assume that labor and financial markets are frictionless.

Our main result is that *so-so automation of junior tasks immiserizes*: when automation of junior tasks comes with small cost savings, marginal improvements in its efficiency reduce the economy's long-run output. The intuition is as follows. Workers care not only about how much they earn over their lifetimes, but also about when they earn it. Automating junior tasks backloads labor income over the life cycle. When automation is "so-so," i.e., its cost savings are small, it raises senior wages by as much as it decreases junior wages.[1] Because workers discount future income, this shift reduces the present value of earnings in careers that rely on experience. In response, workers move out of such careers. This reallocation lowers long-run output because the marginal worker has strictly higher lifetime earnings—and thus higher lifetime marginal product—in experience-intensive careers (to compensate for a more backloaded earnings profile).

Whether junior automation raises or lowers long-run output depends on the balance between two opposing forces. On the one hand, automation has a productivity effect that pushes the production possibility frontier outward. On the other, it generates a reallocation effect that drives workers away from experience-intensive careers. When automation technologies generate sufficiently large

[1] We adopt the term "so-so automation" from Acemoglu and Restrepo (2019).

cost savings, the productivity effect dominates the reallocation effect. However, at the point where automation is just efficient enough to be adopted, the productivity effect is negligible and the reallocation effect dominates. Automation technologies that induce only modest cost savings thus decrease long-run output. In other words, so-so automation of junior jobs immiserizes.

Importantly, immiseration is not a sign of inefficiency. The competitive equilibrium is Pareto efficient. Any policy that prevents immiseration must thus hurt at least some workers. In the laissez-faire equilibrium, automation benefits workers who are already senior at the time of adoption: they receive a higher senior wage without having borne a lower junior wage earlier in life. This gain for the incumbent generation comes at the cost of future generations. Welfare in the new stationary equilibrium is lower for workers with a comparative advantage in experience-intensive careers and may even be lower for all workers.

The immiseration result is robust to a range of extensions. It survives relaxing assumptions regarding the production technology, preferences, experience accumulation, financial markets, and workers' life cycle. Perhaps surprisingly, financial frictions do not necessarily amplify the effects of automation. By affecting equilibrium interest rates and workers' ability to smooth consumption, they can either dampen or amplify the decline in output resulting from so-so junior automation.

We use our framework to quantitatively explore the aggregate effects of automation by robots. We calibrate the model to the U.S. economy in 1980, extend it to allow for automation of both junior and senior tasks, and interpret the traditional sector as being out of the labor force. Measuring which tasks robots automate, we find that junior tasks are more exposed than senior ones. Because robots disproportionately automate junior tasks, the reallocation induced by wage backloading dominates the direct productivity gains when cost savings are small. For realistic cost savings from robots, the total output effect is positive. But the reallocation out of the labor force significantly dampens this effect and almost completely dissipates the growth in market output (GDP). These findings can help explain sluggish economic growth, the reduction in labor force participation, and the steepening of the wage-age profile.

Lastly, we find empirical support for the model's key predictions. We use measures of exposure to robot automation by occupation and classify occupations as junior or senior based on the experience of their workers. From there, we construct industry-level measures of exposure to junior- and senior-task automation. We derive the outcomes of interest from U.S. Census and Current Population Survey data. Consistent with the model's key mechanism, we find that industries where automation is concentrated in junior tasks experience larger declines in employment, increases in the average age of their employees, and a steepening of the wage-age profile.

Related literature. This paper incorporates experience accumulation into a model of task-based production where capital substitutes for labor (e.g., Zeira, 1998; Acemoglu and Autor, 2011; Acemoglu and Restrepo, 2018; Jones and Tonetti, 2026; Martinez, 2025). Existing work studies how automation changes the allocation of production across tasks or firms and its implications for productivity, wages, and growth. By contrast, we emphasize a complementary human-capital channel. Because performing junior tasks is a prerequisite for performing senior tasks later in life, automating junior tasks affects not only the allocation of current production but also the future supply of experienced workers, with potentially adverse consequences for long-run output.[2]

Our paper is related to recent work on apprenticeship, training, and automation (Garicano and Rayo, 2026; Ide, 2025; Afrouzi et al., 2026). These papers show that automating junior tasks can reduce skill accumulation because contracting or coordination frictions prevent private incentives from reflecting the social value of learning. We show that such frictions are not necessary for immiseration. Even with competitive labor and financial markets and a Pareto-efficient equilibrium, junior-task automation can reduce steady-state output by backloading earnings and shifting workers away from experience-intensive careers.

Beraja and Zorzi (2025) show that automation can be inefficiently fast when workers face reallocation and borrowing frictions. In their model, automation generates transitional costs: workers need time to adjust, but once the transition is complete the economy reaches an efficient higher-output steady state. By contrast, in this paper the gains from junior-task automation are concentrated in the short run. Workers who are already senior when automation occurs benefit from higher senior wages without having borne the lower junior wage earlier in life. The adverse effects emerge later, as future cohorts face weaker incentives to acquire experience.

Our paper applies the central insight of the overlapping-generations literature

[2] Althoff and Reichardt (2026) also consider a task-based model in which technical change affects human capital accumulation, but with an entirely different, more quantitative focus.

that individuals at different stages of the life cycle can have conflicting interests (Samuelson, 1958; Diamond, 1965). Junior-task automation benefits workers who have already accumulated the experience required for senior occupations while reducing the incentive of younger and future workers to pursue experience-intensive careers.[3] Our mechanism is therefore most closely related to those in Sachs and Kotlikoff (2012); Sachs et al. (2015); Benzell et al. (2018). Relative to these papers, we study how junior-task automation affects career choices rather than capital accumulation. This shift in focus yields our main result that so-so junior automation is immiserizing, facilitates our quantitative exercise, and allows us to test the theory's central mechanism empirically.

More broadly, our paper is related to the Dutch disease literature, which studies how favorable productivity shocks or resource discoveries induce labor reallocation with adverse long-run consequences (Corden and Neary, 1982; Corden, 1984). In that literature, resource booms contract sectors that generate learning-by-doing or other externalities (Wijnbergen, 1984; Krugman, 1987; Torvik, 2001). While the immiseration described in this paper is conceptually related, it does not result from production externalities. Instead, junior automation can lower the return to acquiring experience in a Pareto-efficient economy because it backloads earnings, reducing the economy's human capital stock.[4]

Outline. Section 2 presents the framework. Sections 3 and 4 characterize the equilibrium and develop our main results. Section 5 considers extensions to the baseline model. Section 6 quantitatively explores robots' aggregate effects in light of the theory. Section 7 presents empirical evidence on the differential effects of junior- and senior-task automation. Section 8 concludes. All proofs are in Appendix A.

[3]The overlapping-generations framework has generated a number of influential insights, including the possibility of valued fiat money (Samuelson, 1958), dynamic inefficiency (Diamond, 1965), sunspots (Cass and Shell, 1983), and rational bubbles (Tirole, 1985). Our paper contributes a different insight: automation can reduce long-run output even though the competitive equilibrium remains Pareto (and thus dynamically) efficient.

[4]Our result also echoes the broader idea of *immiserizing growth* introduced by Bhagwati (1958), who showed that economic growth can reduce welfare through adverse movements in the terms of trade. More recently, Benigno et al. (2025) show that abundant capital inflows can reduce long-run productivity by reallocating resources away from innovative activities. While the mechanisms are entirely different, these papers and ours share the broader insight that favorable shocks can generate adverse aggregate outcomes once the induced equilibrium responses are taken into account.

2 The Model

We begin by describing our model, in which experience accumulation is central to the labor market, and technical change—through task automation—affects the returns to such experience.

2.1 Environment

Overlapping generations and preferences. Time is discrete and indexed by $t = 0, 1, 2....$ The economy is populated by overlapping generations of workers who live for two periods. Each generation has a unit mass, and the set of workers born at date t is denoted by I_t. A worker $i \in I_t$ has lifetime utility:

$$U_t^i = u(c_{t,t}^i) + \beta \cdot u(c_{t,t+1}^i), \tag{1}$$

where $c_{t,t'}^i \geq 0$ denotes the consumption of worker i from generation t at date t' and $\beta \in (0, 1)$ is the workers' discount factor. More generally, for any variable x, we let $x_{t,t'}^i$ denote its value for worker $i \in I_t$ at date t'. We assume workers' preferences can be represented by a CRRA utility function:[5]

$$u(c) = \frac{c^{1-\gamma} - 1}{1 - \gamma}, \quad \gamma \geq 0.$$

Technology. Each worker is endowed with one unit of labor in each period of life. Labor can be supplied either to a "modern" sector or to a "traditional" sector.

Output in the modern sector is produced competitively according to:

$$y_t^M = (S_t)^\alpha \cdot (J_t + k_t)^{1-\alpha}, \quad \alpha \in (0, 1)$$

where $S_t \geq 0$ denotes labor input (in efficiency units) employed in "senior" tasks—i.e., those that require experience—and $J_t \geq 0$ denotes human labor input in the remaining, "junior" tasks. k_t indicates an automation input that the firm can use to substitute for human labor in producing junior tasks.[6]

[5] For $\gamma = 1$, we set $u(c) = \log(c)$. We generalize our main results to the broader class of increasing and weakly concave utility functions in Section 5.

[6] We use the Cobb-Douglas production function primarily for ease of exposition. Later, in Section 5, we extend our results to a more general class of production functions.

We impose the following assumption to ensure that there is a premium to experience in the modern sector:

Assumption 1 $\alpha > \frac{1}{2}$.

The automation technology allows firms to convert $\chi \cdot k_t$ units of the consumption good at date t into k_t efficiency units of junior labor, where $\chi > 0$. Automation, therefore, acts as a perfect substitute for junior labor in production, effectively expanding the economy's supply of junior labor at a constant marginal cost χ. In the main analysis, we assume that the cost of automating senior tasks is prohibitive. This allows us to isolate a form of technical change that selectively expands the supply of junior labor. We contrast this later with the case where senior tasks are automated, which has markedly different implications. Moreover, in the quantitative exercise in Section 6, we allow for both junior and senior tasks to be automatable.

Output in the traditional sector is produced competitively according to:

$$y_t^T = L_t,$$

where $L_t \geq 0$ denotes efficiency units of labor input in that sector.

Occupations, tasks, and comparative advantage. Workers are heterogeneous in their productivity in the modern sector. Each worker $i \in I_t$ draws ψ^i from a continuous distribution $F(\cdot)$, with support $(0, \infty)$ and $\int_0^\infty \psi dF(\psi) < \infty$. The productivity ψ scales up a worker's effective units of labor in the modern sector.[7] Each worker is equally productive in the traditional sector, so that ψ captures a worker's comparative advantage in the modern sector.

A key feature of the economy is that experience is accumulated through work in the modern sector and determines access to experience-intensive tasks later in life. In each period, worker $i \in I_t$ chooses an occupation:

$$o_{t,t'}^i \in \{J, S, T\},$$

where J and S denote work in the modern sector performing junior and senior tasks, respectively, while T denotes work in the traditional sector.

[7] Productivity heterogeneity ensures a unique equilibrium in pure strategies. In particular, workers sort across sectors according to a cutoff rule, avoiding mixed strategies that would otherwise be required if all workers were ex ante identical.

Let $e^i_{t,t'} \in \{0,1\}$ denote whether worker $i \in I_t$ has accumulated modern-sector experience by date t'. Young workers enter the labor market without experience:

$$e^i_{t,t} = 0.$$

Experience is gained by working in junior tasks in the modern sector when young:

$$e^i_{t,t+1} = \mathbf{1}\{o^i_{t,t} = J\}.$$

Given occupation and experience, effective labor supply is:

$$\ell^i_{t,t'} = \begin{cases} \psi^i & \text{if } o^i_{t,t'} = J, \\ \psi^i \cdot e^i_{t,t'} & \text{if } o^i_{t,t'} = S, \\ 1 & \text{if } o^i_{t,t'} = T. \end{cases} \tag{2}$$

Thus, experience is sector-specific: only those who work in the modern sector when young as juniors can access experience-intensive (senior) jobs when old. This creates a life-cycle trade-off: working in the modern sector when young yields lower current returns but enables access to higher-paying senior jobs later on.[8]

Labor market. There is a perfectly competitive labor market. At date t, firms take as given the wages per efficiency unit of labor—denoted by w^T_t, w^S_t, and w^J_t in the traditional sector, senior tasks, and junior tasks, respectively—and demand labor to produce output. Given wages, workers choose where to supply their labor.

Financial market. There is also a perfectly competitive financial market in which workers trade claims to future consumption. We let R_t denote the gross interest rate between dates t and $t+1$, i.e., borrowing one unit of the consumption good at date t requires a repayment of R_t units at date $t+1$.

Worker's optimization problem. A worker $i \in I_t$ chooses occupations $\{o^i_{t,t}, o^i_{t,t+1}\}$ and borrows b^i_t (or saves, when negative) to maximize their lifetime utility sub-

[8] Section 5 discusses an extension where we allow for young workers to be productive in senior tasks too.

ject to the budget constraints:

$$c^i_{t,t} \leq w_t^{o^i_{t,t}} \cdot \ell^i_{t,t} + b^i_t, \tag{3}$$

$$c^i_{t,t+1} \leq w_{t+1}^{o^i_{t,t+1}} \cdot \ell^i_{t,t+1} - R_t \cdot b^i_t, \tag{4}$$

where $\ell^i_{t,t}$ and $\ell^i_{t,t+1}$ are worker i's effective units of labor defined in (2) and w^o_t is the wage per effective unit of labor in occupation $o \in \{J, S, T\}$.

2.2 Equilibrium

Having defined the environment, we now define a competitive equilibrium.

Definition 1 (Competitive Equilibrium) *Given an initial stock of experienced labor $\{\psi^i, e^i_{-1,0}\}_{i\in I_{-1}}$, a competitive equilibrium consists of sequences of prices $\{w^J_t, w^S_t, w^T_t, R_t\}_t$ and allocations $\{c^i_{t,t}, c^i_{t,t+1}, o^i_{t,t}, o^i_{t,t+1}, b^i_t\}_{i,t}$ and $\{J_t, S_t, L_t, k_t\}_t$, such that:*

- *Given prices, workers maximize lifetime utility in (1) subject to (2), (3) and (4);*
- *Given wages, firms maximize profits when allocating inputs to tasks;*
- *Labor and asset markets clear at every date:*

$$\begin{aligned}
J_t &= \int_{\{i\in I_t : o^i_{t,t}=J\}} \ell^i_{t,t}\, di + \int_{\{i\in I_{t-1} : o^i_{t-1,t}=J\}} \ell^i_{t-1,t}\, di, \\
S_t &= \int_{\{i\in I_t : o^i_{t,t}=S\}} \ell^i_{t,t}\, di + \int_{\{i\in I_{t-1} : o^i_{t-1,t}=S\}} \ell^i_{t-1,t}\, di, \\
L_t &= \int_{\{i\in I_t : o^i_{t,t}=T\}} \ell^i_{t,t}\, di + \int_{\{i\in I_{t-1} : o^i_{t-1,t}=T\}} \ell^i_{t-1,t}\, di, \\
0 &= \int_{\{i\in I_t\}} b^i_t\, di.
\end{aligned}$$

In what follows, we focus primarily on the stationary equilibria (steady states) of the economy, as our main results concern the long-run effects of automation. We therefore begin by characterizing the economy's steady states and how they vary with the cost of automation. Section 4 subsequently studies the transition dynamics induced by technological change.

Definition 2 (Stationary Equilibrium) *A stationary equilibrium is a competitive equilibrium in which all prices and allocations are constant over time.*

We next establish that the economy admits a unique stationary equilibrium. We then characterize this equilibrium by showing how occupational choices and the equilibrium interest rate are jointly determined.

Proposition 1 (Existence and Uniqueness) *A stationary equilibrium exists, and it is generically unique.*[9]

Stationary equilibrium wages are pinned down by technology. In any steady state, there is an equal number of juniors and seniors employed in the modern sector.[10] Competitive factor pricing thus implies that equilibrium wages are:

$$w^J = \min\{\chi, 1-\alpha\} \qquad \text{and} \qquad w^S = \alpha \cdot \left(\frac{1-\alpha}{w^J}\right)^{\frac{1-\alpha}{\alpha}}.$$

When $\chi \geq 1-\alpha$, junior tasks are not automated, and junior workers receive a share $1-\alpha$ of output per efficiency unit of labor in the modern sector. By contrast, when $\chi < 1-\alpha$, firms automate junior tasks, and junior wages are pinned down by the automation cost χ. Similarly, traditional sector wages are pinned down by technology: $w^T = 1$.

Two conditions together determine the stationary equilibrium allocation of workers across sectors and the interest rate that clears the financial market.

First, workers choose occupations to maximize the present value of income. For a given interest rate R, there exists a cutoff worker $\bar{\psi}$ who is indifferent between entering the modern and traditional sectors:

$$\bar{\psi} \cdot \left(w^J + \frac{w^S}{R}\right) = 1 + \frac{1}{R}. \tag{5}$$

This condition equates the discounted lifetime labor income associated with the two sectors for the marginal worker. As the wage profile in the modern sector is more backloaded than in the traditional sector, i.e., $w^J < w^S$, condition (5) induces a positive relationship between R and $\bar{\psi}$, depicted by the upward-sloping Labor Market curve in Figure 1. Intuitively, because the modern sector

[9]By generically unique, we mean unique except for a non-generic set of parameters. Namely, when $\gamma = 0$, at $R = \beta^{-1}$ workers are indifferent over the time path of consumption, giving rise to a continuum of equilibrium borrowing and saving decisions and, hence, consumption profiles. This indeterminacy is immaterial for our results, however, as all equilibrium objects of interest are uniquely determined.

[10]Since we have assumed that $\alpha > \frac{1}{2}$, senior tasks pay a premium and all experienced workers perform senior tasks in equilibrium.

offers more delayed compensation, it is less attractive when the interest rate is high. When the interest rate increases, the marginal worker must thus be characterized by a stronger comparative advantage in the modern sector.

Second, the interest rate is such that the supply of savings meets the demand for credit in the financial market. In equilibrium, workers in the traditional sector are the savers, whereas workers in the modern sector are the borrowers. For a given cutoff worker $\bar{\psi}$, financial market clearing therefore requires that:

$$F(\bar{\psi}) \cdot \left[1 - \omega(R) \cdot \left(1 + \frac{1}{R}\right)\right] = \int_{\bar{\psi}}^{\infty} \psi \, dF(\psi) \cdot \left[\omega(R) \cdot \left(w^J + \frac{w^S}{R}\right) - w^J\right], \quad (6)$$

where $\omega(R) \equiv R/[R + (\beta \cdot R)^{\frac{1}{\gamma}}]$ denotes the share of discounted lifetime labor income that a worker consumes when young.[11] The left-hand side of equation (6) corresponds to aggregate savings by workers in the traditional sector, while the right-hand side corresponds to aggregate borrowing by workers in the modern sector. This condition induces a negative relationship between R and $\bar{\psi}$, depicted by the downward-sloping Financial Market curve in Figure 1.[12] Intuitively, when more workers enter the modern sector, i.e., $\bar{\psi}$ decreases, the mass of borrowers relative to savers increases. Financial market clearing therefore requires a higher interest rate to incentivize workers to save more (or borrow less).

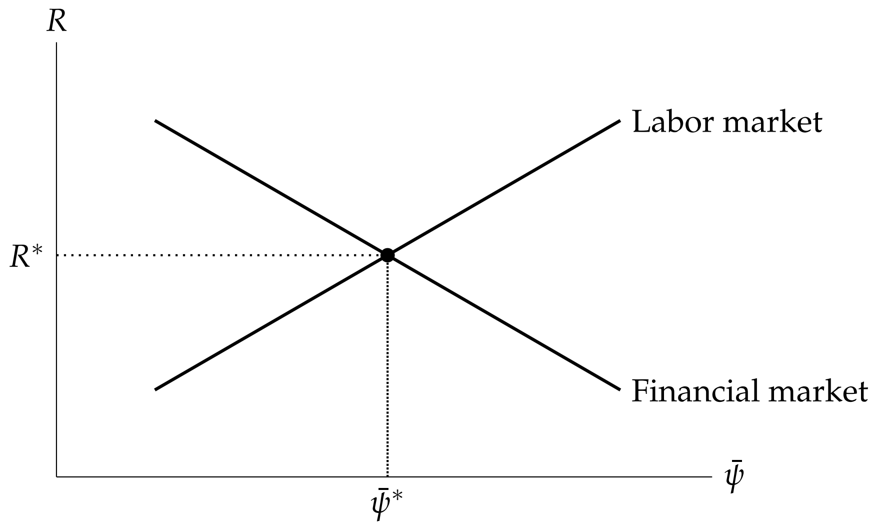
The intersection of the two schedules pins down the equilibrium cutoff worker $\bar{\psi}^*$ and the interest rate R^*. Together, these objects fully characterize the unique stationary equilibrium. In the next sections, we study how the equilibrium responds to changes in technology, first by characterizing comparative statics across stationary equilibria and then by analyzing the associated transitional dynamics. Before turning to this analysis, however, we establish that the steady state provides a natural point of departure: it is stable under the economy's equilibrium dynamics.

Proposition 2 (Stability) *The stationary equilibrium is locally stable: for any initial stock of experienced labor induced by a cutoff of $\bar{\psi}_{-1}$ in a neighborhood of $\bar{\psi}^*$, there is a unique path along which the economy converges to the stationary equilibrium.*

[11]When $\gamma = 0$: $\omega(R) = 1$ if $R < \frac{1}{\beta}$, $\omega(R) = 0$ if $R > \frac{1}{\beta}$, and $\omega(R) \in [0,1]$ if $R = \frac{1}{\beta}$.

[12]The relationship is downward sloping over the relevant range $\beta^{-1} \leq R \leq \beta^{-1} \cdot \left(w^S/w^J\right)^{\gamma}$. If $R < \beta^{-1}$, all workers would borrow, contradicting market clearing. Conversely, if $R > \beta^{-1} \cdot \left(w^S/w^J\right)^{\gamma}$, all workers would save, again contradicting market clearing.

Figure 1: Stationary Equilibrium Determination



Notes: R is the interest rate. $\bar{\psi}$ is the marginal worker's comparative advantage in the modern sector. Workers enter the modern sector iff $\psi \geq \bar{\psi}$, so a larger $\bar{\psi}$ implies a smaller modern sector.

3 Immiseration

We now study how automation affects the stationary equilibrium of the economy. Our main result is that *so-so automation is immiserizing*. We begin by defining so-so automation and immiseration formally.

Definition 3 (So-so Automation) *So-so automation is a marginal reduction in the automation cost χ at the adoption threshold $\chi = 1 - \alpha$.*

A reduction in χ to below $1 - \alpha$ implies that automation inputs replace junior tasks previously performed by human workers. In this sense, it is automation.[13] However, when χ is only just below $1 - \alpha$, automation is only marginally more cost-efficient than human labor. In this sense, the automation is "so-so."

To define immiseration, we first provide a definition of output.

Definition 4 (Output) *Output is the economy's total production net of automation costs:*

$$Y_t = y_t^T + y_t^M - \chi \cdot k_t.$$

[13] While we do not explicitly model automation as an expansion in the set of tasks that can be feasibly performed with the automation input, as is common in the literature (e.g., Acemoglu and Restrepo, 2018), our analysis is equivalent to studying how the effects of such technological change affecting the junior task depend on how productive the automation technology is. For the quantitative exercise in Section 6, we adapt the model so that a subset of junior and senior tasks is automatable.

Because the economy cannot borrow or save in the aggregate, output equals aggregate consumption. In equilibrium, output is equal to the sum of wages earned by workers, as constant returns to scale imply that firms make zero profits.

Immiseration is a reduction in output due to technical change.

Definition 5 (Immiseration) *Technical change is immiserizing if it reduces stationary-equilibrium output.*

The remainder of this section builds toward our main result that so-so automation is always immiserizing. The following lemma is the first step in that direction. It shows that so-so automation decreases the junior wage exactly as much as it increases the senior wage.

Lemma 1 (So-so Automation Rotates Wages) *So-so automation rotates wages while leaving their sum unchanged:*

$$\left.\frac{dw^J}{d\chi}\right|_{\chi=(1-\alpha)^-} = 1 \quad \textit{and} \quad \left.\frac{dw^S}{d\chi}\right|_{\chi=(1-\alpha)^-} = -1.$$

This result follows from profit maximization and competitive factor pricing. A modern-sector firm's problem is:

$$\pi^M(\chi) = \max_{S,J,k} \left\{ y^M(S, J+k) - \chi \cdot k - w^S \cdot S - w^J \cdot J \right\}.$$

When automation inputs are used in the stationary equilibrium, the envelope theorem implies that:

$$\frac{d\pi^M}{d\chi} = -k - \frac{dw^J}{d\chi} \cdot J - \frac{dw^S}{d\chi} \cdot S.$$

Competition implies zero profits before and after the technological change, so:

$$\frac{d\pi^M}{d\chi} = 0.$$

At the adoption threshold, as $k \to 0$, the wage gain of the seniors must thus equal the wage loss of the juniors:

$$S \cdot \left.\frac{\partial w^S}{\partial \chi}\right|_{\chi=(1-\alpha)^-} = -J \cdot \left.\frac{\partial w^J}{\partial \chi}\right|_{\chi=(1-\alpha)^-}.$$

When automation is adopted, junior wages equal the marginal cost of using the automation technology, i.e., $w^J = \chi$, and thus $\frac{\partial w^J}{\partial \chi}|_{\chi=(1-\alpha)^-} = 1$. Since the stationary equilibrium has an equal number of juniors and seniors, i.e., $J = S$, it follows that $\frac{\partial w^S}{\partial \chi}|_{\chi=(1-\alpha)^-} = -1$. Thus, as automation becomes profitable, it rotates wages by lowering junior wages and raising senior wages one-for-one.

We next show that so-so automation reduces employment in the modern sector as a result of the backloading of earnings.

Lemma 2 (So-so Automation Shrinks the Modern Sector) *So-so automation reduces employment in the modern sector:*

$$\frac{d\bar{\psi}^*}{d\chi}\Big|_{\chi=(1-\alpha)^-} < 0.$$

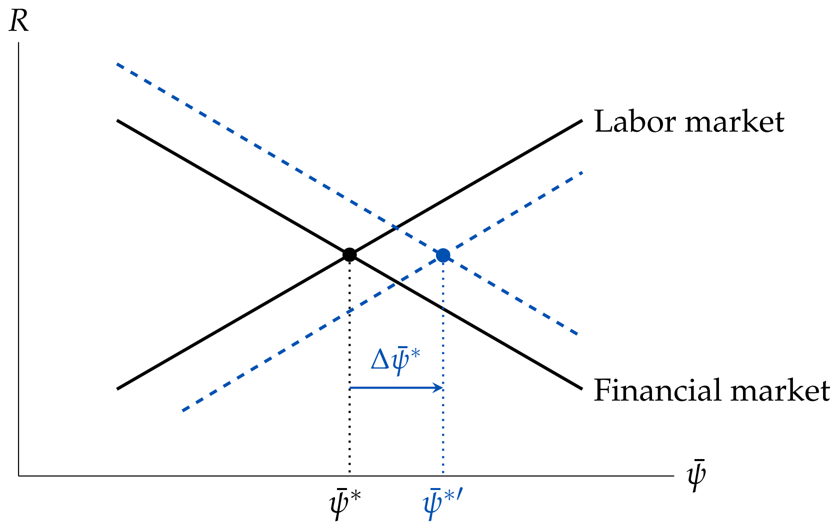
The intuition is illustrated in Figure 2. So-so automation rotates wages in the modern sector by lowering earnings when young and raising earnings when old, without affecting average earnings (Lemma 1). Since workers value earlier earnings more than later earnings (as $R^* > 1$), this reallocation of earnings over the life cycle makes the modern sector less attractive. As a result, the marginal worker must have a stronger comparative advantage in the modern sector for any given interest rate, shifting the Labor Market curve to the right. At the same time, the greater backloading of earnings increases borrowing demand by modern-sector workers, shifting the Financial Market curve to the right. Both forces push workers away from the modern sector and into the traditional sector.

Finally, this shrinkage of the modern sector reduces steady-state output. Equation (5) shows that a marginal worker is paid the same in the modern and traditional sectors *in present value terms*. Hence, their average wage is strictly higher in the sector where they earn a larger share of their income later in life. Formally, from the labor market indifference condition (5), together with the interest rate being above one, and the positive experience premium, $w^S > w^J$, it follows that:

$$\bar{\psi}^* \cdot \left(w^J + w^S\right) > 2 \cdot w^T.$$

The marginal worker $\bar{\psi}^*$ thus sees a reduction in their average wage as so-so automation pushes them into the traditional sector. Average wages of the inframarginal workers are not affected (by Lemma 1). Therefore, with fewer workers in the modern sector, total wages decline. Since a worker's average wage

Figure 2: So-So Automation Shrinks the Modern Sector



Notes: R is the interest rate. $\bar{\psi}$ is the marginal worker's comparative advantage in the modern sector. Workers enter the modern sector iff $\psi \geq \bar{\psi}$, so a larger $\bar{\psi}$ implies a smaller modern sector.

equals their contribution to stationary-equilibrium output, output decreases too.

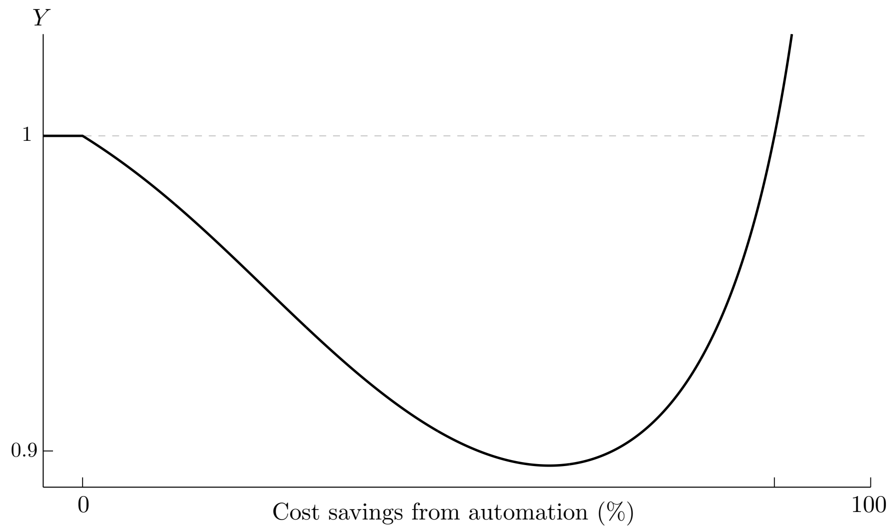
The theorem below formalizes our main result.

Theorem 1 (So-so Automation Immiserizes) *So-so automation is always immiserizing. In particular, there exists a* $\underline{\chi} < 1 - \alpha$ *such that stationary-equilibrium output is strictly lower when the cost of automation satisfies* $\chi \in (\underline{\chi}, 1 - \alpha)$ *than when* $\chi \geq 1 - \alpha$.

We note that the technical change considered here strictly expands the economy's production possibility frontier: the pre-automation allocation remains technologically feasible after automation becomes available. Immiseration arises because workers choose occupations based on the discounted present value of earnings rather than their average wage. By backloading earnings in the modern sector, automation makes experience-intensive careers less attractive, reducing employment in the very sector where technological progress occurs.

The immiseration result is thus qualitatively different from the predictions of the now-standard task-based models of automation (Acemoglu and Restrepo, 2018, 2019). In those models, even so-so automation always increases output. Whether wages fall depends on how strongly automation reduces labor's share of the pie (the "displacement effect") relative to how much the overall pie grows (the "productivity effect"). Instead, in this model so-so automation reduces the size of the pie itself.

Figure 3: So-So Automation Immiserizes



Notes: This figure depicts output relative to its pre-automation level as a function of cost savings from automation $1 - \chi/(1-\alpha)$. Worker ability ψ is log-normal with mean $\mathbb{E}[\psi] = 3$ and variance $\mathrm{Var}[\psi] = 1/2$. The remaining parameters are $\alpha = 2/3$, $\beta = 4/5$, and $\gamma = 2$.

Figure 3 illustrates the process of immiseration that occurs as automation becomes efficient enough to be adopted. As long as $\chi > 1 - \alpha$, automation is not used in equilibrium, so local changes in its efficiency have no effect on output. Once the automation cost χ falls just below $1 - \alpha$, marginal improvements in the efficiency of the automation technology reduce output. The economy thus enters an immiseration region in which technological progress lowers output, eventually reaching a trough. As automation becomes sufficiently productive, the direct productivity gains start dominating the reallocation effect, and output begins to rise with further improvements in technology.

Proposition 3 (Great Automation Drives Growth) *Sufficiently productive automation always increases output. In particular, there exists a $\bar{\chi} < 1 - \alpha$ such that stationary-equilibrium output is strictly higher when $\chi < \bar{\chi}$ than when $\chi \geq 1 - \alpha$.*

The immiserizing nature of so-so automation extends beyond the specific assumptions adopted here for tractability. As we show in Section 5, the arguments underlying Theorem 1 do not rely on the Cobb–Douglas production function, CRRA preferences, or the assumption that workers only live for two periods.[14]

[14]Our conclusions would also be unchanged if firms could offer enforceable long-term wage contracts. Competition would equate the present value of workers' compensation to the present value of their marginal products, and frictionless financial markets would imply that workers are indifferent to the timing of payments conditional on that present value.

Rather, the key ingredient is that automation disproportionately substitutes for tasks performed early in the life cycle and thus backloads labor income.

The mechanism also makes clear that the consequences of automation depend on which tasks are automated. Our baseline model isolates the automation of junior tasks to highlight its effects on experience accumulation. Automation of senior tasks has the opposite implications. By raising the rewards for juniors, senior-task automation *frontloads* labor income and increases the attractiveness of experience-intensive careers even if the productivity gains from automation are small. Workers therefore move into the modern sector, raising aggregate output. Whether so-so automation raises or lowers long-run output thus depends on the stage of the career ladder at which it substitutes for labor.

4 Transitions and Welfare Consequences

We now study the transition following the adoption of so-so automation. Suppose the economy is initially in a stationary equilibrium without automation and that, at date $t = 0$, the automation cost unexpectedly falls marginally below the adoption threshold $1 - \alpha$. Throughout, we focus on the locally stable equilibrium dynamics characterized in Proposition 2. Along this path, the cutoff worker $\bar{\psi}_t^*$, the interest rate R_t^*, wages, and occupational choices jump immediately to their new stationary-equilibrium values. By contrast, the stock of experienced workers is fixed on impact, as it is determined by occupational choices made before automation was adopted.

Proposition 4 (Transition Dynamics) *Along the locally stable equilibrium path after so-so automation:*

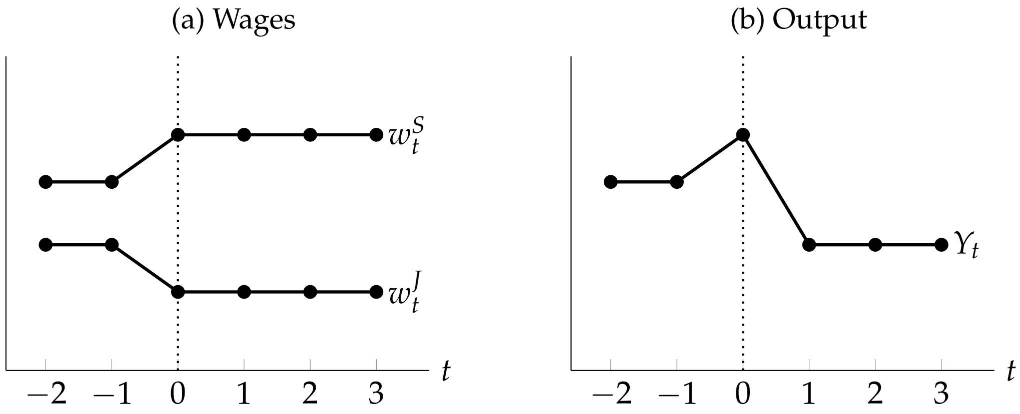
1. *The cutoff worker $\bar{\psi}_t^*$, the interest rate R_t^*, and wages immediately jump to their new stationary-equilibrium values.*

2. *Output initially rises and then reaches a new stationary-equilibrium level that is lower than before.*

3. *The initial cohort of experienced workers strictly benefits from automation.*

Figure 4 illustrates these dynamics. Junior and senior wages immediately jump to their new stationary-equilibrium levels. While prices and occupational

Figure 4: Wages and Output During the Transition



Notes: t indexes time, with so-so automation adopted at $t = 0$.

choices adjust on impact, the economy initially inherits the larger stock of senior workers accumulated before automation was adopted. The combination of the existing stock of experience with a lower cost of junior input increases modern-sector output. Further, as the marginal young worker shifts to the traditional sector, the output in that sector increases too. At the time of adoption, total output thus exceeds its initial stationary-equilibrium level. Once occupational choices adjust and the inherited stock of human capital is depleted, output falls to a lower steady-state level. In this sense, the immiserizing effects of automation are not immediately visible in aggregate output.

The path of wages also shows that the transition creates winners. The initial cohort of senior workers in the modern sector benefits as it receives the higher senior wage induced by automation without having borne the lower junior wage earlier in life. Thus, although so-so automation reduces stationary-equilibrium output, it strictly benefits this cohort.

We now turn to the welfare of workers in the new stationary equilibrium.

Proposition 5 (Welfare Effects) *So-so automation reduces stationary-equilibrium welfare for all modern-sector workers and possibly for all workers.*

All modern-sector workers are made worse off because so-so automation backloads their wages. The fact that the marginal worker moves to the traditional sector reflects this welfare loss. The effect on traditional-sector workers' welfare is ambiguous. Being savers, these workers are also worse off if the interest rate falls. If the interest rate instead rises, they are better off. Both situations can occur in equilibrium.

Propositions 4 and 5 together raise the question of whether policy can prevent immiseration without creating losers. As we show next, the answer is no.

Proposition 6 (Pareto Efficiency) *Given an initial stock of experienced labor, the competitive equilibrium is Pareto efficient.*

Proposition 6 shows that immiseration does not require an underlying inefficiency. In our frictionless benchmark, the decline in long-run output reflects an efficient equilibrium response to the changing timing of labor income rather than a distortion that can be eliminated without creating losers. This does not imply that there is no role for policy. Policies may be desirable on redistributive grounds, and additional frictions—such as financial constraints or other market imperfections—may both amplify the effects of automation and create scope for Pareto-improving interventions. Our point is simply that such frictions are not necessary for technical change to reduce long-run output.

5 Extensions and Robustness

We consider several extensions of the baseline environment, including more general preferences and production technologies, the presence of financial frictions, and longer-lived workers. We show that our main result, that so-so automation of junior tasks is immiserizing, is robust to these alternative specifications and generalizations. We discuss these extensions briefly below. More detailed analysis of each extension can be found in Appendix B.

General Preferences and Technologies. The immiseration result does not depend on the Cobb–Douglas and CRRA specifications used in the baseline model. On the production side, it is sufficient for the technology to exhibit constant returns to scale, complementarity between junior and senior tasks, and a positive experience premium. Under these conditions, junior automation continues to rotate earnings toward later stages of the career. On the preference side, the result requires only that utility be increasing and weakly concave. Weak concavity implies that shifting income from youth to old age weakly increases workers' desired borrowing and therefore raises the attractiveness threshold for entering the modern sector. Consequently, both the Labor Market and Financial Market schedules shift in the same direction as in Figure 2, reducing modern-sector employment and output. CRRA preferences are useful primarily for ensuring uniqueness of the stationary equilibrium, not for generating immiseration.

Financial Frictions. The baseline model assumes that workers can freely borrow against future labor income. Because modern-sector careers feature a strongly backloaded wage profile, one might expect borrowing constraints to amplify the immiserizing effects of automation. This intuition is incomplete, however. To show this, we introduce limited pledgeability of labor income in the spirit of Hart and Moore (1994). Tighter borrowing constraints reduce the attractiveness of modern-sector careers and discourage experience accumulation. But they also reduce borrowing demand and lower equilibrium interest rates. Since modern-sector workers are net borrowers, the resulting decline in interest rates partially offsets the reduced attractiveness of modern-sector careers. Consequently, financial frictions affect immiseration through two opposing channels. While so-so automation remains immiserizing, financial frictions may either attenuate or amplify the decline in output relative to the frictionless benchmark.

Beyond Two-Period Careers. The baseline model adopts a stark life-cycle structure in which workers spend one period as juniors and one period as seniors. We show that the immiseration result obtains in a perpetual-youth economy à la Yaari (1965) and Blanchard (1985), where workers face uncertain lifetimes and accumulate experience over the course of their careers. Although the environment is substantially richer, the equilibrium remains governed by the interaction of a Labor Market and a Financial Market schedule, as in Figure 2. So-so automation continues to backload labor income by reducing the return to early-career work relative to later-career work. Consequently, entry into modern careers declines, the modern sector contracts, and aggregate output falls, just as in the baseline economy.

Direct Path to Senior Occupations. The baseline model assumes that experience acquired in junior jobs is the only path to senior careers. We relax this by allowing inexperienced workers to enter senior occupations directly, though at lower productivity than workers who accumulate experience through apprenticeship. This alternative path does not eliminate immiseration and can instead amplify it. As automation backloads the earnings from apprenticeship, workers become willing to sacrifice the productivity gains from experience accumulation in exchange for the flatter earnings profile offered by direct entry. Thus, the same force that reallocates workers from the modern to the traditional sector in our baseline model also operates within the modern sector, shifting workers from apprenticeship toward less productive direct-entry careers. This additional reallocation can deepen the decline in output before sufficiently productive automation eventually raises it.

6 A Quantitative Exploration

We extend our baseline economy to explore the aggregate effects of automation by robots. The only departure from the model studied before is that we allow for a subset of both junior and senior tasks to be subject to automation and calibrate their automatability to match data on tasks' exposure to robots. We calibrate the model so that the modern and traditional sectors reflect market work and home production, respectively.

6.1 A Task-Based Model With Junior and Senior Automation

Technology. As in the baseline model, modern sector output is produced by combining senior and junior inputs:

$$y_t^M = \left(X_t^S\right)^{\alpha} \cdot \left(X_t^J\right)^{1-\alpha},$$

where we again assume that $\alpha > \frac{1}{2}$ so that there is an experience premium. Unlike in the baseline model, junior and senior inputs are bundles of a continuum of tasks combined in fixed proportions:

$$X_t^o = \min_{\tau \in [0,1]} x_t^o(\tau) \text{ for } o \in \{J, S\}.$$

Tasks $\tau \leq I^o$ are automatable and can be produced with labor or with the automation technology, while tasks $\tau > I^o$ require labor:

$$x_t^o(\tau) = \begin{cases} L_t^o(\tau) + k_t^o(\tau) & \text{if } \tau \leq I^o, \\ L_t^o(\tau) & \text{if } \tau > I^o, \end{cases}$$

where $L_t^o(\tau)$ is labor in efficiency units and $k_t^o(\tau)$ is the automation input (Acemoglu and Autor, 2011; Acemoglu and Restrepo, 2019, 2020). The automation technology converts χ^o units of final good output into one efficiency unit of occupation-o labor.

The rest of the model. Besides the task-based production function, the model is identical to that in Section 2, summarized below:

- Workers live for two periods, have CRRA preferences with elasticity of intertemporal substitution $\frac{1}{\gamma}$, and a discount factor β;
- Each worker $i \in I_t$ draws their effective units of labor supply in the modern sector ψ^i from a distribution $F(\cdot)$;
- Performing senior tasks in the modern sector requires experience as a junior, while the traditional sector does not reward experience;
- There are perfectly competitive labor and financial markets;
- Workers choose their occupations to maximize lifetime utility.

The model is equivalent to the model in Section 2 when all junior tasks, but no senior tasks, are automatable, i.e., $I^J = 1$ and $I^S = 0$.

6.2 Equilibrium

The competitive equilibrium of this model is defined analogously to the baseline version in Section 2. The only difference is that firms are now allocating factors to a continuum of tasks in both occupations. They do so to minimize costs. We again focus on the stationary equilibrium of the model.

Task allocation. Firms allocate factors to tasks to maximize profits. Let $k^o \equiv \int_0^{I^o} k^o(\tau)d\tau$ be the total automation input allocated to occupation $o \in \{J, S\}$. Optimal allocation under Leontief implies that firms produce the same amount of each task and that the total output of an occupation equals the total efficiency units of labor and automation input allocated to that occupation:

$$X^J = J + k^J \text{ and } X^S = S + k^S,$$

where J and S are the total efficiency units of human junior and senior labor input, respectively. The firm thus solves the following maximization problem:

$$\max_{\{J,S,X^J,X^S\}} \quad \left(X^S\right)^{\alpha} \cdot \left(X^J\right)^{1-\alpha} - w^J \cdot J - w^S \cdot S - \chi^J \cdot (X^J - J) - \chi^S \cdot (X^S - S)$$

$$\text{subject to} \quad X^J \cdot \left(1 - I^J\right) \leq J \leq X^J \quad \text{and} \quad X^S \cdot \left(1 - I^S\right) \leq S \leq X^S.$$

If the wage w^o is below the cost of automation χ^o for some $o \in \{J, S\}$, the firm assigns all tasks to humans in that occupation, regardless of automatability. In other words, the automation threshold I^o is not binding in that case. If the wage is above χ^o, firms only allocate labor to non-automatable tasks.

Wages. The total wage bill earned by workers in each occupation is the total expenditure accruing to the input that the occupation produces after subtracting the automation costs:

$$w^J \cdot J = (1-\alpha) \cdot y^M - \chi^J \cdot \left(X^J - J\right),$$
$$w^S \cdot S = \alpha \cdot y^M - \chi^S \cdot \left(X^S - S\right).$$

6.3 Quantifying Robots' Aggregate Effects

Calibration. For the purpose of this exercise, we interpret the traditional sector as home production, measured as being out of the labor force. Home production is a natural real-world counterpart to the traditional sector because it arguably provides limited returns to experience. This mapping also allows us to quantify how robots affected growth in market output and labor force participation.[15]

Table 1 shows the calibrated values of the parameters and how we set them. Since we want to consider the effects of robots, we calibrate the parameters to match the U.S. economy in 1980, before widespread robot adoption (Acemoglu and Restrepo, 2020). For calibration purposes, we thus assume that neither junior nor senior tasks are automatable in the baseline, i.e., $I^o_{1980} = 0$ for both $o \in \{J, S\}$. We assume the modern-sector productivity distribution $F(\cdot)$ is Fréchet with shape parameter κ and scale parameter A. The scale parameter A governs the average productivity of workers in market work (relative to home

[15]Besides the reallocation between market and home production, one could also consider how robots reallocated workers across different industries *within* the market sector. For simplicity, we abstract from such reallocation here.

production), while $\kappa > 1$ governs the strength of comparative advantage and thus the elasticity of labor supply.

Table 1: Calibration

Parameter		Target			
Symbol	Value	Moment	Equation	Value	Source
α	0.654	Experience premium	$\frac{2\alpha-1}{1-\alpha}$	88.7%	Lagakos et al. (2018)
γ	3	Elast. of intertemporal subst.	$\frac{1}{\gamma}$	$\frac{1}{3}$	Havránek (2015)
κ	2.86	Labor supply elasticity	Eq. (M.1)	0.75	Chetty et al. (2011)
A	3.45	Share out of labor force, 1980	Eq. (M.2)	10.4%	Census
β	0.92	Annualized interest rate	Eq. (M.3)	10%	Federal Reserve

Notes: A period is taken to be twenty years, e.g., from age 20 to 39 and from age 40 to 59. The share of people out of the labor force in 1980 refers to men within that age range. We set the target interest rate to match the cost of unsecured consumer credit, a natural empirical counterpart to borrowing against future labor income. The Federal Reserve's Consumer Credit release reports nominal rates on personal loans of around 10–12 percent, with substantially higher rates on revolving credit, suggesting that a 10 percent real interest rate is a reasonable benchmark.[16]

Measuring Junior and Senior Automation by Robots. To measure junior and senior tasks' exposure to robots, we first classify occupations as "junior" and "senior" based on the amount of experience they require.[17] We classify an occupation as senior if it has above-median experience requirements, weighted by employment. We then compute the share of tasks in each occupation that Garg et al. (2026) classify as "automatable" by robots.[18] From there, we set I^J_{Robots}

[16]The moments targeted are the following functions of the parameters:

$$\frac{\partial \ln\left(1 - F(\bar{\psi}^*)\right)}{\partial \ln\left(w^J + w^S/R\right)} = -\kappa \cdot \frac{F(\bar{\psi}^*) \cdot \ln F(\bar{\psi}^*)}{1 - F(\bar{\psi}^*)} \tag{M.1}$$

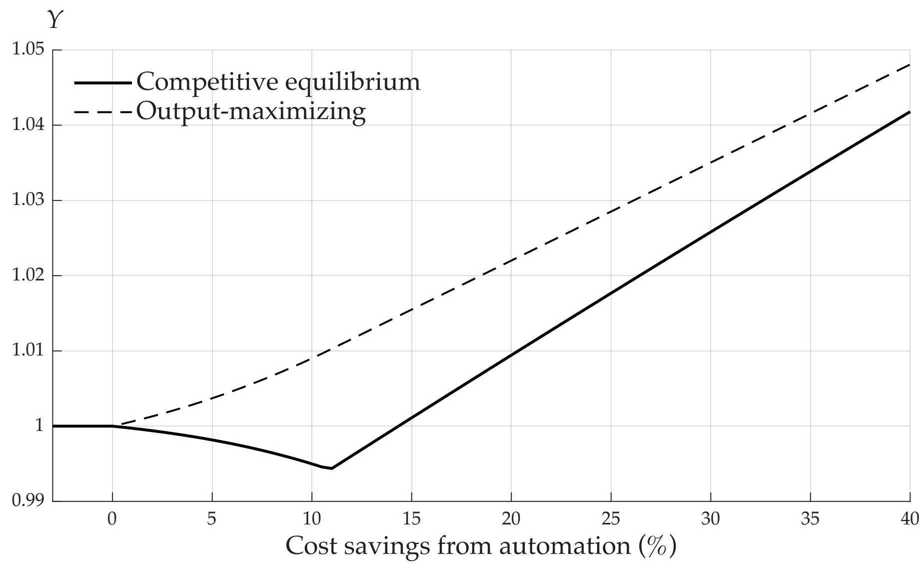
$$F(\bar{\psi}^*) = \exp\left(-\left(\frac{A \cdot \left(1 - \alpha + \frac{\alpha}{R}\right)}{1 + \frac{1}{R}}\right)^{\kappa}\right) \tag{M.2}$$

$$R = \frac{1}{\beta} \cdot \left(\frac{\alpha \cdot \int_{\bar{\psi}^*}^{\infty} \psi \, dF(\psi) + F(\bar{\psi}^*)}{(1-\alpha) \cdot \int_{\bar{\psi}^*}^{\infty} \psi \, dF(\psi) + F(\bar{\psi}^*)}\right)^{\gamma} \tag{M.3}$$

[17]We use O*NET's Education, Training, and Experience module that contains information on the years of related work experience required for each occupation. For each occupation, we compute the average value reported across respondents. The questionnaire can be found here.

[18]As a measure of occupation-level exposure to robots, we use the share of tasks exposed to automation through the "physical execution" channel, which captures tasks exposed to

Figure 5: The Output Effect of Robot Automation



Notes: This figure shows the effect of robot automation on output, depending on the cost savings per automatable task. The shares of automatable junior tasks and senior tasks are 0.21 and 0.06, respectively. The solid line shows the effect on output under the competitive equilibrium given the calibrated parameters shown in Table 1. The dashed line shows the effect of the technical change on the maximum steady-state output the economy can achieve. Cost savings for juniors and seniors are assumed to be the same.

and I^S_{Robots} to the average shares of junior and senior tasks that are automatable by robots, respectively.

Junior occupations were more exposed to automation by robots than senior ones. Quantitatively, we find $I^J_{\text{Robots}} = 0.21$ and $I^S_{\text{Robots}} = 0.06$. We use our calibrated model to gauge what this implies for the aggregate effects of robots.

Results. Figure 5 shows robots' effects on aggregate output, depending on the cost savings they induced. Since robots disproportionately automated junior tasks, the logic behind Theorem 1 applies: when robots are so-so, the reallocation effect induced by wage backloading in the modern sector dominates the direct productivity effect, inducing a decrease in output. The dashed line in Figure 5 shows the output effect that arises if workers were to maximize the average wage over their lifetime rather than their discounted lifetime wages.[19]

substitution by "robotics, mechanical actuation, and embodied systems that physically perform the task, such as warehouse picking or assembly automation" (Garg et al., 2026).

[19]In the competitive equilibrium, workers maximize average lifetime wages if the gross interest rate is one. We achieve this by setting $\beta = 1$ and $\gamma = 0$, while keeping the other parameters as in Table 1.

The shape of the output effect reveals the economics behind it. When cost savings are low enough, the junior automation threshold I^J_{Robots} is not binding, and junior workers perform both automatable and non-automatable tasks. In this region, the wages are pinned down by the cost of using the automation technology χ^J. As cost savings increase, the automation threshold eventually becomes binding, inducing a kink. Once the economy hits the threshold, junior workers concentrate on the non-automatable tasks and any further efficiency gains to the automation technology only increase their marginal product. From that point onward, further cost savings increase output.

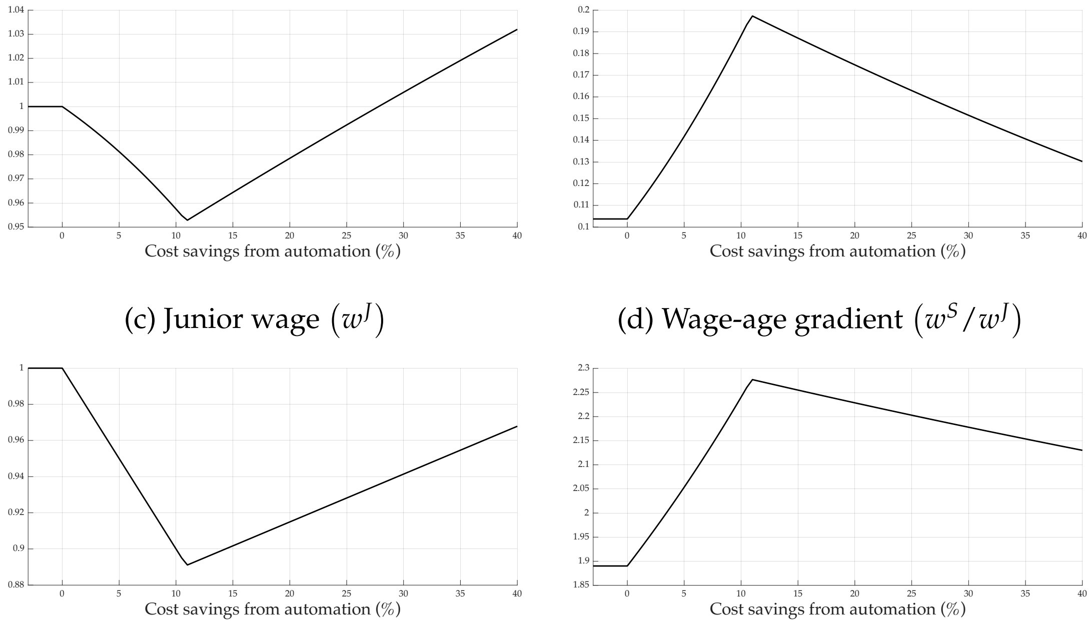
Acemoglu and Restrepo (2020) estimate that cost savings from robots were around 30%. At that level, Figure 5 implies a positive output effect of about 2.6%. Absent the reallocation mechanism emphasized in this paper, the same technical change would have raised output by roughly 3.5% (as reflected by the dashed line showing growth under output maximization). Wage backloading thus dissipates around a quarter of the potential gain.

While Figure 5 shows output growth when accounting for home production, such production is not captured in GDP growth. Steady-state modern sector output—closest to standard measures of economic output—barely increases even under large cost savings. Figure 6a shows that robots' effect on GDP growth amounts to only around half a percentage point even at 30% cost savings. These results can explain the robust GDP growth of the 1980s and 1990s and the subsequent stagnation (e.g., Antolin-Diaz et al., 2017): the transition path highlighted in this paper predicts a boom while the current generation of experienced workers is complemented by technology, followed by a decline as incentives to accumulate experience fall.[20]

The model also speaks to the decline in labor force participation. By backloading earnings, junior automation pushes a significant share of workers out of the labor force: with 30% cost savings, the model predicts a 4.5 percentage-point fall in the participation rate (Figure 6b). Robotization of predominantly junior tasks could thus have contributed to the observed fall in labor force participation: the share of 20-to-59-year-old men out of the labor force rose from 10.4% in 1980 to 15.0% in 2019. While other forces are likely to have also spurred a decline in male labor force participation (e.g., Krueger, 2017), this exercise shows that junior automation offers an additional, and quantitatively powerful, explanation.[21]

[20] Also see Aghion et al. (2023); De Ridder (2024) for alternative explanations for this pattern.
[21] Di Giacomo and Lerch (2026) find reduced-form evidence that robot automation lowered

Figure 6: The Effects of Robot Automation on Other Economic Outcomes



(a) GDP $\left(y^M\right)$ (b) Out of labor force $\left(F\left(\bar{\psi}^*\right)\right)$

(c) Junior wage $\left(w^J\right)$ (d) Wage-age gradient $\left(w^S/w^J\right)$

Notes: This figure shows, clockwise, the effect on modern sector output, or GDP; the share of people out of the labor force; the wage-age gradient; and the junior wage. GDP and the junior wage are shown relative to their pre-automation levels.

Lastly, the model can further help rationalize the observed increase in the wage-age gradient. Career earnings growth in the U.S. roughly doubled between 1980 and 2017 (Deming, 2021, Figure 5). Junior automation by robots can offer an explanation: Figure 6d shows an increase in the wage-age gradient for market work. At the same time, this paper shows that such wage backloading may have had negative effects on labor force participation, output, and welfare.

The exercise above is a simple back-of-the-envelope calculation, illustrating the quantitative relevance and applicability of the theory. Since we kept the model purposefully simple, one should exercise caution when interpreting its quantitative implications. For instance, we abstract from various frictions that may be quantitatively important, such as borrowing frictions. Further, some industries within the modern (market) sector have seen stronger, and more junior-biased, robot automation than others. Section 7 shows reduced-form evidence that this led to reallocation within the market sector, which could either strengthen or dampen the effects shown here.

labor force participation.

7 Empirical Evidence

In this section, we use differences across U.S. industries in the exposure of junior and senior tasks to robotization to empirically test the theory's main mechanisms. The theory predicts that when automation is concentrated in the junior tasks, a sector becomes less attractive to workers because it backloads earnings. In support of this theory, we find that industries where junior tasks were disproportionately exposed to automation by robots saw a relative decrease in employment, an increase in the average age, and a steepening of the wage-experience profile.

7.1 Data and Empirical Specification

We use microdata from the U.S. Census and the American Community Survey from 1970 to 2020. These data provide, for a representative sample of workers, their industry, occupation, age, and wage. We conduct the analysis at the level of the 1990 Census industry classification, which is consistently available across all years. For each industry and year, we construct total employment, the total wage bill, and the average worker's age.

We rely on occupation-level robot exposure measures constructed by Garg et al. (2026). This measure is construcuted using large language model prompts and correlates strongly with other commonly used measures of exposure to robots (that do not rely on LLMs), such as those constructed by Webb (2019).

Using these measures of occupational exposure, we first construct a measure of each *industry*'s overall exposure as the average occupation-level exposure across people working in this industry. That is:

$$\text{Automation}_s \equiv \frac{1}{n_s} \sum_{i:s^i_{80}=s} \text{OccAutomation}_{o^i_{80}},$$

where s indexes the industry (or sector), s^i_{80} is the 1990 Census industry group in which worker i was active in 1980, $n_s \equiv \sum_i \mathbb{1}[i : s^i_{80} = s]$ is the number of workers in sector s, OccAutomation_o is occupation o's exposure to automation, and o^i_{80} is worker i's occupation in the 1980 Census.[22]

[22]We use the 1990 occupational classification system, which is consistently available in the census data.

We then construct measures of the degree to which an industry's automation exposure is concentrated in the more junior tasks. Our baseline measure of the junior bias of automation is the negative of the correlation between a worker's age and their exposure. That is, for sector s:

$$\text{JuniorBias}_s = -\text{Corr}\left(\text{OccAutomation}_{o^i_{80}}, \text{Age}^i_{80} \mid s^i_{80} = s\right),$$

where Age^i_{80} is the age of the worker in the 1980 Census. Being a correlation, this measure is bounded between -1 and 1. If it is one, it means that there is a perfect negative correlation between age and exposure within the industry, so that the exposure is strongly biased to juniors. An advantage of this measure is that it captures how automation is distributed across tasks separately from how much automation the industry faces overall.

We show that the results are robust to alternative measures of junior bias. Specifically, we also show results measuring junior bias as the difference between the exposure of workers below versus above the industry-specific median age. We use the industry-specific median age to ensure that both measures are computed based on equally sized populations. Moreover, we show results when junior bias is instead based on the within-industry correlation between occupations' experience requirements and exposure to robotization.

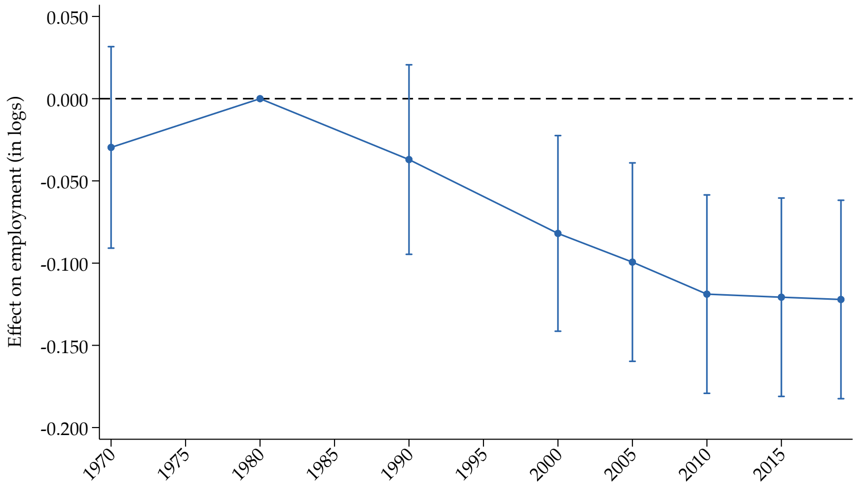
We estimate the following difference-in-differences specification:

$$\log y_{st} = \sum_{t'} \mathbf{1}\{t' = t\} \cdot (\beta_{t'} \cdot \text{JuniorBias}_s + \gamma_{t'} \cdot \text{Automation}_s) + \mu_s + \lambda_t + \varepsilon_{st}, \tag{7}$$

where y_{st} is the outcome of interest for industry s in year t and μ_s and λ_t are industry and year fixed effects, respectively. Both the junior bias and the measure of overall automation exposure are fixed at their 1980 values and interacted with year indicators, with 1980 as the omitted base year.

The coefficients of interest are the $\beta_{t'}$, which reflect how the outcome of an industry is correlated with the degree to which its automatable tasks are junior tasks, holding total exposure fixed. The model predicts that automating junior tasks depresses sector employment relative to automating senior tasks, so that we expect these parameters to be negative.

Figure 7: Employment Effects of Junior Bias in Robot Exposure



Notes: This figure reports estimates of the parameters $\beta_{t'}$ in equation (7). The dependent variable is an industry's log employment. The coefficients are normalized by the standard deviation of the independent variable so that they reflect effects per standard deviation of junior bias. The regression controls for year and industry fixed effects and for the overall exposure of the industry to automation by robots, interacted with year. The bars reflect 90% confidence intervals.

7.2 Results

In line with the theory's prediction, we find that exposure to robots has had a more negative effect on industry-level employment when it was biased to junior tasks. Figure 7 reports the estimates of the regression in equation (7) with log employment as the dependent variable. Junior bias is correlated with a substantial decline in employment after 1980. Quantitatively, the effects mean that an industry for which the junior bias was one standard deviation stronger saw an additional decline of about 10% in employment.

The result that employment decreases more with junior than with senior automation is robust to various alternative specifications. First, it is robust to using the difference between junior and senior exposure as the independent variable as opposed to the correlation between age and exposure (Figure C.1). Second, we obtain similar effects when we replicate the exercise using robot exposure measures constructed by Webb (2019) (Figure C.2). Lastly, it is robust to measuring exposure using 1990 as the baseline instead of 1980 as in Acemoglu and Restrepo (2020) (Figure C.3).

Further, we find that junior-biased automation predicts an increase in the average age of workers in the industry. We use the same specification as in equation (7), except for changing the outcome variable to the log average age. Figure C.4 shows positive effects of junior bias in robotization on the industry-specific average age. These results are consistent with our model's prediction along the transition path where junior entry is reduced relative to the existing stock of seniors.

Lastly, we find evidence that exposure to junior-biased robotization led to wage backloading. We use data from the CPS on a given worker's weekly earnings in two consecutive years. The longitudinal aspect of these data allows us to compute each worker's annual wage growth. We regress this wage growth on the junior bias in automation in the worker's industry, interacted with time as in equation (7).[23] We find that junior-biased automation predicts an increase in wage growth, implying a steepening of the wage schedule (Figure C.5).

8 Conclusion

This paper studies how junior automation affects workers' incentives to accumulate experience and, ultimately, the economy's output. In our model, performing junior tasks is necessary to acquire the skills to perform senior tasks. Automating junior tasks reduces the marginal product of junior work and thus *backloads* wages toward old age. When the automation does not come with large cost savings, i.e., it is so-so, this wage backloading makes experience accumulation less attractive. Workers thus move away from experience-intensive careers, reducing the future supply of experienced workers and thus long-run output. We show that this result is robust to a variety of extensions, including more general technologies and preferences, financial frictions, and longer life cycles. Through an exploration of robots' aggregate effects, we show that the theory can have quantitatively important implications for labor force participation and economic growth. We also provide empirical evidence consistent with the model's central prediction: industries in which exposure to automation by robots is concentrated in junior tasks saw larger employment declines, an aging workforce, and a steeper wage-age profile.

[23] We control for age, sex, and time fixed effects, cluster standard errors at the industry level, and only include workers if they were employed in the same industry in both years. To compute wages, we divide weekly earnings by the usual number of hours worked.

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Appendix

A Proofs and Derivations for Sections 2-4

Proof of Proposition 1. Since both the Labor Market and Financial Market schedules, given by (5) and (6), define continuous maps from $\bar{\psi}$ to R, to establish existence and uniqueness, it is sufficient to show that one of them is downward sloping in $(\bar{\psi}, R)$-space while the other is upward sloping.

The labor market condition (5) implies:

$$R = \frac{\bar{\psi} \cdot w^S - 1}{1 - w^J \cdot \bar{\psi}}$$

which yields an upward-sloping curve in $(R, \bar{\psi})$ since $\bar{\psi} \cdot w^S > 1$ and $w^J \cdot \bar{\psi} < 1$.

The financial market condition (6) implies:

$$\frac{(\beta \cdot R)^{\frac{1}{\gamma}} - 1}{w^S - (\beta \cdot R)^{\frac{1}{\gamma}} \cdot w^J} = \frac{\int_{\bar{\psi}}^{\infty} \psi \, dF(\psi)}{F(\bar{\psi})}.$$

Since the left-hand side of this equation is increasing in R, while the right-hand side is decreasing in $\bar{\psi}$, equation (6) induces a negative relationship between R and $\bar{\psi}$. This establishes uniqueness.

To prove existence, note that for $\bar{\psi} = \frac{1}{w^S}$, $R = 0$ and there must be strictly more demand for borrowing than supply of savings. Also, when $\bar{\psi} \to \frac{1}{w^J}$, $R \to \infty$ and there must be excess supply of savings. Since both equations are continuous, existence follows from the intermediate value theorem. ■

Proof of Proposition 2. We establish the result separately for the case with and without automation.

Case without automation: $\chi > 1 - \alpha$. The dynamic equivalent of the financial market conditions implies:

$$\begin{aligned} \mathcal{F}(\bar{\psi}_{t-1}, \bar{\psi}_t, \bar{\psi}_{t+1}) &\equiv \left((\beta \cdot R_t)^{\frac{1}{\gamma}} - 1 \right) \cdot F(\bar{\psi}_t) - \left(w_{t+1}^S - (\beta \cdot R_t)^{\frac{1}{\gamma}} w_t^J \right) \cdot \int_{\bar{\psi}_t}^{\infty} \psi dF(\psi) \\ &= 0, \end{aligned}$$

where prices w_t^J, w_{t+1}^S and R_t are functions of $\bar{\psi}_{t-1}$, $\bar{\psi}_t$, $\bar{\psi}_{t+1}$ only. The dynamics of the economy can therefore be characterized by the second-order difference equation in $\bar{\psi}_{t-1}$, $\bar{\psi}_t$, and $\bar{\psi}_{t+1}$.

We establish local stability by analyzing the stability of the first-order approximation to the nonlinear dynamic system:

$$\left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t-1}}\right|_* \cdot (\bar{\psi}_{t-1} - \bar{\psi}^*) + \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_t}\right|_* \cdot (\bar{\psi}_t - \bar{\psi}^*) + \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t+1}}\right|_* \cdot (\bar{\psi}_{t+1} - \bar{\psi}^*) = 0.$$

where $\cdot|_*$ indicates the derivative is evaluated at the steady state.

Some algebra yields:

$$\begin{aligned}
\left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t+1}}\right|_* &= \frac{(\beta \cdot R^*)^{\frac{1}{\gamma}}}{R^* \cdot \gamma} \cdot \left.\frac{\partial R_t}{\partial \bar{\psi}_{t+1}}\right|_* \cdot \left(F(\bar{\psi}^*) + w^J \cdot \int_{\bar{\psi}^*}^{\infty} \psi dF(\psi)\right) - \left.\frac{\partial w_{t+1}^S}{\partial \bar{\psi}_{t+1}}\right|_* \cdot \int_{\bar{\psi}^*}^{\infty} \psi dF(\psi) \\
\left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_t}\right|_* &= \frac{(\beta \cdot R^*)^{\frac{1}{\gamma}}}{R^* \cdot \gamma} \cdot \left.\frac{\partial R_t}{\partial \bar{\psi}_t}\right|_* \cdot \left(F(\bar{\psi}^*) + w^J \cdot \int_{\bar{\psi}^*}^{\infty} \psi \, dF(\psi)\right) \\
&\quad + f(\bar{\psi}^*) \cdot \left[(\beta \cdot R^*)^{\frac{1}{\gamma}} - 1\right] - \left.\frac{\partial w_{t+1}^S}{\partial \bar{\psi}_t}\right|_* \cdot \int_{\bar{\psi}^*}^{\infty} \psi dF(\psi), \\
&\quad + (\beta \cdot R^*)^{\frac{1}{\gamma}} \cdot \left.\frac{\partial w_t^J}{\partial \bar{\psi}_t}\right|_* \cdot \int_{\bar{\psi}^*}^{\infty} \psi \, dF(\psi) + \left(w^S - (\beta \cdot R^*)^{\frac{1}{\gamma}} \cdot w^J\right) \cdot \bar{\psi}^* \cdot f(\bar{\psi}^*), \\
\left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t-1}}\right|_* &= \frac{(\beta \cdot R^*)^{\frac{1}{\gamma}}}{R^* \cdot \gamma} \cdot \left.\frac{\partial R_t}{\partial \bar{\psi}_{t-1}}\right|_* \cdot \left(F(\bar{\psi}^*) + w^J \cdot \int_{\bar{\psi}^*}^{\infty} \psi \, dF(\psi)\right) \\
&\quad + (\beta \cdot R^*)^{\frac{1}{\gamma}} \cdot \left.\frac{\partial w_t^J}{\partial \bar{\psi}_{t-1}}\right|_* \cdot \int_{\bar{\psi}^*}^{\infty} \psi dF(\psi).
\end{aligned}$$

For stability of the linearized system, we require one eigenvalue to be within the unit circle and the other outside the unit circle. In other words, we require the characteristic polynomial:

$$H(\lambda) = \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t+1}}\right|_* \cdot \lambda^2 + \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_t}\right|_* \cdot \lambda + \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t-1}}\right|_*$$

to have exactly one root between -1 and 1.

To show that the linearized system is locally stable, it is sufficient that $H(1)$ and $H(-1)$ have opposite signs. To see why, note that the opposite signs of $H(1)$ and $H(-1)$ imply that $H(\lambda)$ has an odd number of roots within $(-1, 1)$. Since $H(\lambda)$ is quadratic, it has at most two roots and thus exactly one root within

$(-1,1)$.

We use that:

$$\left.\frac{\partial R_t}{\partial \bar{\psi}_{t+1}}\right|_* = \frac{\bar{\psi}^* \cdot \left.\frac{\partial w^S_{t+1}}{\partial \bar{\psi}_{t+1}}\right|_*}{1 - w^J \cdot \bar{\psi}^*},$$

$$\left.\frac{\partial R_t}{\partial \bar{\psi}_t}\right|_* = \frac{w^S + R^* \cdot w^J + \bar{\psi}^* \cdot \left.\frac{\partial w^S_{t+1}}{\partial \bar{\psi}_t}\right|_* + R^* \cdot \bar{\psi}^* \cdot \left.\frac{\partial w^J_t}{\partial \bar{\psi}_t}\right|_*}{1 - w^J \cdot \bar{\psi}^*},$$

$$\left.\frac{\partial R_t}{\partial \bar{\psi}_{t-1}}\right|_* = \frac{R^* \cdot \bar{\psi}^* \cdot \left.\frac{\partial w^J_t}{\partial \bar{\psi}_{t-1}}\right|_*}{1 - w^J \cdot \bar{\psi}^*},$$

$$\left.\frac{\partial w^S_{t+1}}{\partial \bar{\psi}_{t+1}}\right|_* = -\left.\frac{\partial w^S_{t+1}}{\partial \bar{\psi}_t}\right|_* = -(1-\alpha) \cdot w^S \cdot \frac{\bar{\psi}^* \cdot f(\bar{\psi}^*)}{\int_{\bar{\psi}^*}^{\infty} \psi dF(\psi)},$$

$$\left.\frac{\partial w^J_t}{\partial \bar{\psi}_t}\right|_* = -\left.\frac{\partial w^J_t}{\partial \bar{\psi}_{t-1}}\right|_* = \alpha \cdot w^J \cdot \frac{\bar{\psi}^* \cdot f(\bar{\psi}^*)}{\int_{\bar{\psi}^*}^{\infty} \psi dF(\psi)}.$$

From there:

$$\begin{aligned} H(1) &= \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t+1}}\right|_* + \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_t}\right|_* + \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t-1}}\right|_* \\ &= \frac{(\beta \cdot R^*)^{\frac{1}{\gamma}}}{R^* \cdot \gamma} \cdot \left(F\left(\bar{\psi}^*\right) + w^J \cdot \int_{\bar{\psi}^*}^{\infty} \psi \, dF(\psi) \right) \cdot \left(\left.\frac{\partial R_t}{\partial \bar{\psi}_{t+1}}\right|_* + \left.\frac{\partial R_t}{\partial \bar{\psi}_t}\right|_* + \left.\frac{\partial R_t}{\partial \bar{\psi}_{t-1}}\right|_* \right) \\ &\quad + f\left(\bar{\psi}^*\right) \cdot \left((\beta \cdot R^*)^{\frac{1}{\gamma}} - 1 \right) + \left(w^S - (\beta \cdot R^*)^{\frac{1}{\gamma}} \cdot w^J \right) \cdot \bar{\psi}^* \cdot f\left(\bar{\psi}^*\right) \end{aligned}$$

so that:

$$H(1) > 0$$

since:

$$\left.\frac{\partial R_t}{\partial \bar{\psi}_{t+1}}\right|_* + \left.\frac{\partial R_t}{\partial \bar{\psi}_t}\right|_* + \left.\frac{\partial R_t}{\partial \bar{\psi}_{t-1}}\right|_* = \frac{w^S + R^* \cdot w^J}{1 - w^J \cdot \bar{\psi}^*} > 0$$

and

$$1 \leq (\beta \cdot R^*)^{\frac{1}{\gamma}} \leq \frac{w^S}{w^J}.$$

It remains to prove that $H(-1) < 0$. Again, combining terms, we obtain

$$
\begin{aligned}
H(-1) = & \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t+1}}\right|_{*} - \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t}}\right|_{*} + \left.\frac{\partial \mathcal{F}}{\partial \bar{\psi}_{t-1}}\right|_{*} \\
= & \frac{(\beta \cdot R^*)^{\frac{1}{\gamma}}}{R^* \cdot \gamma} \cdot \left(F\left(\bar{\psi}^*\right) + w^J \cdot \int_{\bar{\psi}^*}^{\infty} \psi \, dF(\psi) \right) \left(\left.\frac{\partial R_t}{\partial \bar{\psi}_{t+1}}\right|_{*} - \left.\frac{\partial R_t}{\partial \bar{\psi}_{t}}\right|_{*} + \left.\frac{\partial R_t}{\partial \bar{\psi}_{t-1}}\right|_{*} \right) \\
& - f\left(\bar{\psi}^*\right) \cdot \left((\beta \cdot R^*)^{\frac{1}{\gamma}} - 1 \right) - \left(w^S - (\beta \cdot R^*)^{\frac{1}{\gamma}} \cdot w^J \right) \cdot \bar{\psi}^* \cdot f\left(\bar{\psi}^*\right) \\
& - 2 \left((\beta \cdot R^*)^{\frac{1}{\gamma}} - 1 \right) \cdot \alpha \cdot (1 - \alpha) \cdot \bar{\psi}^* \cdot f\left(\bar{\psi}^*\right)
\end{aligned}
$$

so that

$$H(-1) < 0$$

because

$$\left.\frac{\partial R_t}{\partial \bar{\psi}_{t+1}}\right|_{*} - \left.\frac{\partial R_t}{\partial \bar{\psi}_{t}}\right|_{*} + \left.\frac{\partial R_t}{\partial \bar{\psi}_{t-1}}\right|_{*} = -\frac{w^S + R^* \cdot w^J + 2 \cdot \bar{\psi}^* \cdot \frac{\partial w^S_{t+1}}{\partial \bar{\psi}_t} + 2 \cdot R^* \cdot \bar{\psi}^* \cdot \frac{\partial w^J_t}{\partial \bar{\psi}_t}}{1 - w^J \cdot \bar{\psi}^*} < 0$$

and

$$1 \leq (\beta \cdot R^*)^{\frac{1}{\gamma}} \leq \frac{w^S}{w^J}.$$

The linearized system thus has exactly one eigenvalue within the unit circle. Since the model has one predetermined variable and one forward-looking variable, this linearized system is locally stable. That is, there exists a locally unique path toward the stationary equilibrium. By the Hartman-Grobman theorem, this implies that the nonlinear system is locally stable too.

Case with automation: $\chi < 1 - \alpha$. With automation, wages are pinned down by χ in a neighborhood around the steady state. This implies that wages do not respond locally to changes in entry thresholds and thus

$$
\begin{aligned}
\left.\frac{\partial R_t}{\partial \bar{\psi}_{t+1}}\right|_{*} &= 0 \\
\frac{\partial R_t}{\partial \bar{\psi}_{t}}|_{*} &= \frac{w^S + R^* \cdot w^J}{1 - w^J \cdot \bar{\psi}^*} \\
\frac{\partial R_t}{\partial \bar{\psi}_{t-1}}|_{*} &= 0.
\end{aligned}
$$

The result then follows from the same reasoning as above because it implies that $H(1) > 0$ and $H(-1) < 0$. ■

Proof of Lemma 1. See text. ■

Proof of Lemma 2. See text. ■

Proof of Theorem 1. See text for the proof that the stationary-equilibrium output must be strictly increasing in χ near the automation threshold $\chi = (1-\alpha)^-$. By continuity of output in χ, this implies that there exists a $\underline{\chi} < 1-\alpha$ such that output is strictly lower when the cost of automation satisfies $\chi \in (\underline{\chi}, 1-\alpha)$ than when $\chi > 1-\alpha$. ■

Proof of Proposition 3. It is sufficient to show that stationary-equilibrium output goes to infinity as $\chi \to 0$. When $\chi < 1-\alpha$, senior wages (per efficiency unit of labor) are:

$$w^S = \alpha \cdot \left(\frac{1-\alpha}{\chi}\right)^{\frac{1-\alpha}{\alpha}} \to \infty \text{ as } \chi \to 0.$$

Since output equals total wages, it is sufficient to show that the senior wage bill must go to infinity, i.e., that:

$$w^S \cdot \int_{\bar{\psi}}^{\infty} \psi \, dF(\psi) \to \infty.$$

If $\bar{\psi}$ remains bounded, the result is immediate since $w^S \to \infty$. Thus, suppose instead that $\bar{\psi} \to \infty$ so that $\int_{\bar{\psi}}^{\infty} \psi \, dF(\psi) \to 0$ and $F(\bar{\psi}) \to 1$.

From the Labor Market condition (5), if employment in the modern sector goes to zero, i.e., $\bar{\psi} \to \infty$, while senior wages tend to infinity, i.e., $w^S \to \infty$, the interest rate must tend to infinity too, i.e., $R \to \infty$. The Financial Market condition (6) implies that:

$$\frac{\int_{\bar{\psi}}^{\infty} \psi \, dF(\psi)}{F(\bar{\psi})} = \frac{1 - \omega(R) \cdot \left(1 + \frac{1}{R}\right)}{\omega(R) \cdot \left(w^J + \frac{w^S}{R}\right) - w^J}.$$

Since the denominator is no greater than $\omega(R) \cdot w^S / R$, we obtain:

$$\frac{w^S \cdot \int_{\bar{\psi}}^{\infty} \psi \, dF(\psi)}{F(\bar{\psi})} \geq R \cdot \left(\frac{1}{\omega(R)} - 1 - \frac{1}{R}\right) = (\beta \cdot R)^{1/\gamma} - 1, \tag{8}$$

where we used the expression for $\omega(R)$ defined by Equation (6).[24] Since $R \to \infty$, the right-hand side of (8) tends to infinity too. Since $F(\bar{\psi}) \to 1$:

$$w^S \cdot \int_{\bar{\psi}}^{\infty} \psi \, dF(\psi) \to \infty.$$

Hence, total wages and output must tend to infinity as $\chi \to 0$, which in turn implies that output is higher with automation than without it whenever $\chi \in (0, \bar{\chi})$ for $\bar{\chi}$ small enough. ■

Proof of Proposition 4. From Proposition 2, there exists a unique locally stable equilibrium path converging from the pre-automation steady state to the post-automation steady state. The text constructs an equilibrium in which both the cutoff $\bar{\psi}_t^\star$ and the interest rate $R_t^\star$ jump immediately to their post-automation steady-state values following the adoption of automation. Since this equilibrium converges to the post-automation steady state, uniqueness implies that it coincides with the locally stable path.

Workers who are already senior in the transition period receive the higher senior wage induced by automation without having experienced the lower junior wage earlier in life. Their lifetime income therefore increases, implying that they strictly benefit from so-so automation.

Finally, output rises on impact. The cutoff rises immediately, so some workers who would have entered the modern sector as junior workers instead work in the traditional sector. The marginal worker at the pre-automation cutoff satisfies:

$$\bar{\psi}^* \cdot \left(w^J + \frac{w^S}{R^*} \right) = 1 + \frac{1}{R^*}.$$

Since $w^S > w^J$ and $R^* > 1$, it follows that:

$$\bar{\psi}^* \cdot w^J < 1.$$

Hence the marginal worker produces less than one unit of output as a junior worker in the modern sector but exactly one unit in the traditional sector. The induced reallocation therefore raises output on impact. ■

[24] The expression for $\omega(R)$ is only valid for $\gamma > 0$. But note that for $\gamma = 0$ (linear preferences), the result is immediate since it implies that $R = \frac{1}{\beta}$ so that modern-sector employment cannot go to zero as $w^S \to \infty$.

Proof of Proposition 5. We first show that modern-sector workers must be worse off after so-so automation. Let $U^M(\psi, w^J, w^S, R)$ be the lifetime utility of a worker with productivity ψ in the modern sector when junior and senior wages are w^J and w^S, respectively, and the interest rate is R.

CRRA preferences imply that consumption scales linearly with lifetime income (and thus with ψ). This implies that modern-sector utility increases for all ψ if and only if it increases for any ψ. Thus if $\tilde{U}^M(w^J, w^S, R) \equiv U^M(\psi = 1, w^J, w^S, R)$ declines, $U^M(\psi, w^J, w^S, R)$ declines for all ψ.

Suppose towards contradiction that $\tilde{U}^M(w^J, w^S, R)$ increases after so-so automation. Since the marginal worker moves to the traditional sector (Lemma 2), traditional-sector utility $U^T(R)$ must increase too (by revealed preference). Since traditional-sector utility is increasing in R by the envelope theorem, this implies that R increases. However, when R increases and the senior wage increases by as much as the junior wage decreases, the discounted value of the modern-sector career decreases, and thus utility $\tilde{U}^M(w^J, w^S, R)$ decreases, a contradiction. ■

Lemma 3 *Given an initial stock of experienced labor, let $\{R_t^*\}_{t\geq 0}$ denote the interest rates along the corresponding competitive equilibrium path. Define the associated intertemporal prices as $q_0 = 1$ and $q_{t+1} = \frac{q_t}{R_t^*}$ for all $t \geq 0$. Then:*

$$\sum_{t=0}^{\infty} q_t < \infty.$$

Proof. Let I_t^y and I_t^o denote the average income of the young and old at date t, respectively. Financial market clearing implies that:

$$R_t^* = \frac{1}{\beta} \cdot \left(\frac{I_{t+1}^o}{I_t^y} \right)^{\gamma}.$$

Hence, for every $t \geq 1$:

$$q_t = \prod_{s=0}^{t-1} \frac{1}{R_s^*} = \beta^t \cdot \left(\frac{I_0^y I_1^y \cdots I_{t-1}^y}{I_1^o I_2^o \cdots I_t^o} \right)^{\gamma} = \beta^t \cdot \left(\frac{I_0^y}{I_t^o} \right)^{\gamma} \cdot \left(\prod_{s=1}^{t-1} \frac{I_s^y}{I_s^o} \right)^{\gamma}.$$

Since the old are choosing occupations to maximize their income and they have weakly more experience than the young, they must earn more than the young on average at any given point in time. That is, $I_t^o \geq I_t^y$ for all dates t. Thus:

$$q_t \leq \beta^t \cdot \left(\frac{I_0^y}{I_t^o}\right)^{\gamma}.$$

Finally, every old worker can earn an income of 1 in the traditional sector, so $I_t^o \geq 1$ and I_0^y is finite because total labor income equals date-0 output, which is bounded since $\int \psi \, dF(\psi) < \infty$. Thus, there exists $M < \infty$ such that:

$$\sum_{t=0}^{\infty} q_t \leq M \cdot \sum_{t=0}^{\infty} \beta^t = \frac{M}{1-\beta} < \infty,$$

since we have assumed that $\beta \in (0,1)$. ■

Proof of Proposition 6. Fix an initial mass of experienced old workers and the corresponding competitive equilibrium path. For simplicity, suppose that the initial old enter date 0 without assets or debts. This assumption is inessential: inherited financial positions can be included in their date-0 budget constraints and cancel in the aggregate, as their net supply is zero.

Let $\{R_t^*\}_{t\geq 0}$ denote the interest rates along the corresponding competitive equilibrium path. Define the associated intertemporal prices as follows:

$$q_0 = 1, \qquad q_{t+1} = \frac{q_t}{R_t^*} \quad \text{for all } t \geq 0.$$

By Lemma 3 above, we have $\sum_{t=0}^{\infty} q_t < \infty$. Since $\int \psi dF(\psi) < \infty$, this implies that aggregate consumption, output, and labor income are uniformly bounded. Thus, the present-value aggregates used below are well defined.

The argument below follows the standard proof of the First Welfare Theorem in Chapter 16 of Mas-Colell et al. (1995), adapted to the overlapping-generations structure of our economy.

For a worker $i \in I_t$ born at date $t \geq 0$, let $z_{t,t}^i$ and $z_{t,t+1}^i$ denote their labor income when young and old, respectively, evaluated at the competitive wages. Because workers can borrow and save freely, their sequential budget constraints are equivalent to the present-value constraint:

$$q_t \cdot c_{t,t}^i + q_{t+1} \cdot c_{t,t+1}^i \leq q_t \cdot z_{t,t}^i + q_{t+1} \cdot z_{t,t+1}^i. \tag{9}$$

Each worker chooses consumption and a feasible occupational path to maximize lifetime utility, subject to (9) and the technological constraint that working in senior occupations in the modern sector requires prior junior experience in that sector. An initial old worker $i \in I_{-1}$ takes their inherited experience as given and chooses consumption and a feasible date-0 occupation subject to $c^i_{-1,0} \leq z^i_{-1,0}$.

Suppose, for contradiction, that there exists an alternative feasible allocation, indicated by hats, that respects the initial condition, makes almost every worker weakly better off than under the competitive allocation, and makes a set of workers of positive mass strictly better off. For every worker $i \in I_t$ and $t \geq 0$, individual optimality implies:

$$q_t \cdot \left(\widehat{c}^i_{t,t} - \widehat{z}^i_{t,t}\right) + q_{t+1} \cdot \left(\widehat{c}^i_{t,t+1} - \widehat{z}^i_{t,t+1}\right) \geq 0. \tag{10}$$

If the left-hand side of (10) were negative, the alternative consumption and occupational plan would cost strictly less, at the competitive prices, than the labor income generated by that plan. Hence the plan would lie strictly inside the worker's budget set. Since preferences are locally non-satiated, there would then exist an arbitrarily nearby affordable consumption plan that the worker strictly prefers to the alternative plan. Because the alternative plan already makes the worker weakly better off than the competitive allocation, this nearby plan would be strictly preferred to the competitive allocation, contradicting the optimality of the competitive choice. Moreover, the inequality (10) is strict whenever the worker is strictly better off. Otherwise, the strictly preferred alternative plan would itself be affordable under the worker's equilibrium budget constraint.

The analogous argument for the initially old workers gives:

$$\widehat{c}^i_{-1,0} - \widehat{z}^i_{-1,0} \geq 0 \text{ for all } i \in I_{-1}, \tag{11}$$

with strict inequality whenever that worker is strictly better off. Summing (10) and (11) over workers and across cohorts yields:

$$\int_{I_{-1}} \left(\widehat{c}^i_{-1,0} - \widehat{z}^i_{-1,0}\right) di + \sum_{t=0}^{\infty} \int_{I_t} \left[q_t \cdot \left(\widehat{c}^i_{t,t} - \widehat{z}^i_{t,t}\right) + q_{t+1} \cdot \left(\widehat{c}^i_{t,t+1} - \widehat{z}^i_{t,t+1}\right)\right] di > 0. \tag{12}$$

The inequality is strict because we have assumed that a positive measure of workers is strictly better off.

We next use firms' profit maximization. Let $\widehat{J}_t$, $\widehat{S}_t$, $\widehat{L}_t$, and $\widehat{k}_t$ denote the aggregate inputs induced by the alternative allocation, and let:

$$\widehat{W}_t = w_t^J \cdot \widehat{J}_t + w_t^S \cdot \widehat{S}_t + w_t^T \cdot \widehat{L}_t$$

be the corresponding labor income evaluated at equilibrium wages. At these wages, the equilibrium modern-sector production plan maximizes:

$$S^\alpha \cdot (J+k)^{1-\alpha} - \chi \cdot k - w_t^J \cdot J - w_t^S \cdot S.$$

Because the modern-sector technology has constant returns to scale and equilibrium profits are zero, any alternative production plan satisfies:

$$(\widehat{S}_t)^\alpha \cdot (\widehat{J}_t + \widehat{k}_t)^{1-\alpha} - \chi \cdot \widehat{k}_t \leq w_t^J \cdot \widehat{J}_t + w_t^S \cdot \widehat{S}_t. \tag{13}$$

In the traditional sector, $w_t^T = 1$, so that:

$$\widehat{y}_t^T = w_t^T \cdot \widehat{L}_t. \tag{14}$$

Combining (13) and (14), alternative output net of automation costs satisfies:

$$\widehat{Y}_t \leq \widehat{W}_t.$$

Let $\widehat{C}_t$ denote aggregate consumption at date t. Feasibility requires:

$$\widehat{C}_t \leq \widehat{Y}_t \quad \Longrightarrow \quad \widehat{C}_t - \widehat{W}_t \leq 0 \text{ for every } t \geq 0.$$

Multiplying by q_t and summing across dates yields:

$$\sum_{t=0}^{\infty} q_t \cdot \left(\widehat{C}_t - \widehat{W}_t\right) \leq 0. \tag{15}$$

Note that the left-hand side of (15) equals the left-hand side of (12). But, whereas the latter is strictly positive, the former is weakly negative, a contradiction.

Hence no feasible allocation respecting the initial mass of experienced old workers can make almost every worker weakly better off and a set of workers of positive measure strictly better off. The competitive equilibrium allocation is therefore Pareto efficient. ■

B Details on Extensions

We consider several extensions of the baseline environment, including more general preferences and production functions, financial constraints, and longer-lived households. We show that our main result, that so-so automation of junior tasks is immiserizing, is robust to these alternative specifications and generalizations. We also discuss some additional insights that these extensions provide.

B.1 General Preferences and Technologies

Production functions. The Cobb-Douglas assumption is not necessary for immiseration to occur. It is sufficient that the aggregate production function exhibits constant returns to scale, complementarity between junior and senior tasks, and a positive experience premium.

Let modern output be produced according to a constant-returns-to-scale production function $Y^M(S, J+k)$. Under constant returns to scale, wages depend only on the effective junior-senior task ratio $(J+k)/S$. In a stationary equilibrium without automation, $k=0$, this task ratio is one. Once automation is efficient enough to be used in steady state, the marginal cost of automation pins down the marginal product of junior tasks:

$$w^J = Y_2^M\left(1, \left(\frac{J+k}{S}\right)\right) = \chi,$$

where Y_2^M is the derivative of $Y^M(\cdot,\cdot)$ with respect to the second argument. The automation cost χ thus determines the task ratio and junior and senior wages. The experience premium is positive absent automation if $Y_1^M(1,1) > Y_2^M(1,1)$.

Any CRS production function implies that so-so automation increases the senior wage by as much as it decreases the junior wage. This follows directly from the same envelope argument used to prove Lemma 1, which does not rely on the Cobb-Douglas form, only on constant returns to scale and competitive factor pricing.

From there, the mechanism illustrated in Figure 2 carries over. So-so automation backloads wages in the modern sector, shifting both curves to the right, reducing modern-sector entry and output.

Note that aggregate constant returns to scale are consistent with decreasing returns to scale at the firm level, as long as there is free entry that drives profits to zero. Thus immiseration by so-so automation carries over to such settings too. Absent free entry, automation may generate rents, and the welfare and output effects depend on how those rents are allocated.

Preferences. Immiseration by so-so automation does not depend on CRRA utility. It holds for any increasing and weakly concave utility function.

Preferences affect the stationary equilibrium only through workers' saving and borrowing decisions and thus shape the Financial Market curve in Figure 1. For a general utility function $u(\cdot)$, the Financial Market equation in (6) becomes:

$$-F(\bar{\psi}) \cdot b\,(R, 1, 1) = \int_{\bar{\psi}}^{\infty} b\left(R, \psi \cdot w^J, \psi \cdot w^S\right)\, dF(\psi),$$

where $b(R, w_1, w_2)$ denotes the demand for borrowing when the interest rate is R and the incomes when young and old are w_1 and w_2, respectively:

$$b(R, w_1, w_2) = \arg\max_b \left\{u(w_1 + b) + \beta \cdot u(w_2 - R \cdot b)\right\}.$$

Weak concavity of $u(\cdot)$ is enough to ensure that borrowing demand increases when income is shifted from youth to old age.[25] Since so-so automation generates exactly such a shift, it increases borrowing demand for any given interest rate R. Financial market clearing then requires a smaller mass of borrowers and a higher cutoff $\bar{\psi}$, shifting the Financial Market curve to the right. Since the shape of the Labor Market is not affected by preferences, both equilibrium schedules shift to the right, as in Figure 2, and so-so automation increases $\bar{\psi}^*$ and reduces output.

The immiseration result thus only requires a weakly concave utility function. CRRA is useful to ensure that the stationary equilibrium is unique, for which a concave utility function is not sufficient.

[25] A weakly concave utility function implies that for any $0 < w_1 < w_2$, $R > 0$, and $\epsilon > 0$,

$$b\,(R, w_1 - \epsilon, w_2 + \epsilon) \geq b\,(R, w_1, w_2)\,.$$

For linear utility, optimal borrowing is not uniquely defined. However, in that case the Financial Market curve is horizontal and the rightward shift of the Labor Market curve is sufficient to generate immiseration. Hence, weak concavity suffices.

B.2 Financial Frictions

We formalize the two channels summarized in Section 5 by limiting the pledgeability of senior labor income. In particular, we assume that a worker can pledge at most a fraction $\theta \in [0,1]$ of senior labor income, so that:

$$R_t \cdot b_t^i \leq \theta \cdot \psi^i \cdot w^S.$$

The parameter $\theta \in [0,1]$ captures the degree of financial development. When $\theta = 1$, future labor income is fully pledgeable and the economy coincides with our baseline specification. Lower values of θ tighten borrowing constraints by reducing the fraction of future earnings that can be pledged to investors.

The introduction of financial frictions leaves the structure of the equilibrium characterization largely unchanged. There are, however, two important modifications relative to the baseline model. First, the analog of the indifference condition (5) between the modern and the traditional sectors must now account for the possibility that workers in the modern sector are financially constrained. The occupational cutoff is thus determined by equality of lifetime utility rather than of discounted lifetime income. The resulting Labor Market condition becomes:

$$\bar{\psi} = \left[\frac{c^T(R)^{1-\gamma} + \beta \cdot \left[1 + R - R \cdot c^T(R)\right]^{1-\gamma}}{c^M(R)^{1-\gamma} + \beta \cdot \left[w^S + R \cdot w^J - R \cdot c^M(R)\right]^{1-\gamma}} \right]^{\frac{1}{1-\gamma}}, \tag{16}$$

where:

$$c^T(R) \equiv \omega(R) \cdot \left(1 + \frac{1}{R}\right); \; c^M(R) \equiv \min\left\{\omega(R) \cdot \left(w^J + \frac{w^S}{R}\right), w^J + \frac{\theta \cdot w^S}{R}\right\}.$$

Here, $c^T(R)$ and $c^M(R)$ are the consumption levels (per efficiency unit of labor) of traditional- and modern-sector workers, and $\omega(R)$ is the share of lifetime income consumed if constraints were slack. When constraints bind, young modern-sector workers consume less than in the baseline model, as limited pledgeability prevents them from fully smoothing consumption over the life cycle. As in the baseline model, this condition defines an upward-sloping relationship between $\bar{\psi}$ and R.

Second, the analog of the financial market clearing condition (6), which defines the Financial Market curve, is now given by:

$$F(\bar{\psi}) \cdot \left[1 - c^T(R)\right] = \int_{\bar{\psi}}^{\infty} \psi \, dF(\psi) \cdot \left[c^M(R) - w^J\right]. \tag{17}$$

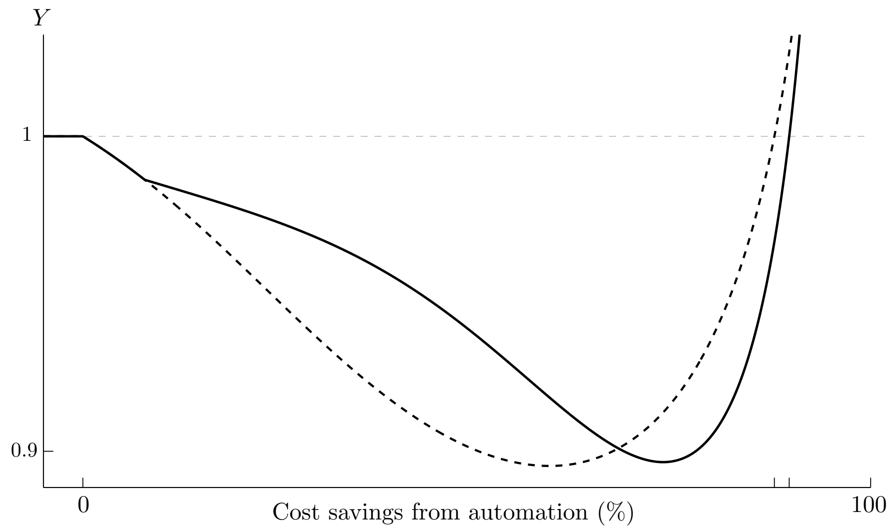
Whereas the savings function $1 - c^T(R)$ of the traditional-sector workers is as before, the borrowing function $c^M(R) - w^J$ is now depressed due to limited pledgeability. Nevertheless, as in the baseline model, this condition yields a downward-sloping relationship between $\bar{\psi}$ and R.

The unique stationary equilibrium is given by the intersection of the Labor Market and Financial Market schedules. The two conditions make transparent how financial frictions affect immiseration. Through the Labor Market condition (16), tighter borrowing constraints reduce the utility value of a modern-sector career because workers cannot fully transfer resources from their high-earning senior years to their low-earning junior years. Holding R fixed, this lowers entry into the modern sector and amplifies the decline in experience acquisition. Through the Financial Market condition (17), tighter borrowing constraints reduce borrowing demand and therefore lower the equilibrium interest rate. Since modern-sector workers are net borrowers while traditional-sector workers are net lenders, the resulting decline in interest rates improves the intertemporal terms of trade faced by the former and offsets the occupational-choice distortion.

Financial frictions therefore affect immiseration through a tension between an occupational-choice distortion and a terms-of-trade effect. Despite this ambiguity, the qualitative effect of automation remains unchanged: a decline in the automation cost shifts both the Labor Market and Financial Market schedules to the right (as in Figure 2), raising the occupational cutoff, reducing modern-sector employment, and lowering stationary-equilibrium output.

Figure B.1 illustrates these forces. The dashed curve corresponds to our baseline economy, while the solid curve corresponds to an economy in which borrowing constraints begin to bind only after the economy enters the immiseration region. Initially, financial frictions attenuate immiseration because the equilibrium-interest-rate effect dominates. As the cost of automation becomes lower, however, the occupational-choice distortion becomes increasingly important and eventually dominates. Consequently, financial frictions first mitigate and later amplify the decline in output relative to the frictionless benchmark.

Figure B.1: Immiseration Under Financial Frictions



Notes: This figure depicts output relative to its pre-automation level as a function of cost savings from automation $1 - \chi/(1-\alpha)$, with financial frictions ($\theta = 1/8$, solid line) and without ($\theta = 1$, dashed line). Both economies are governed by the same preference and technological parameters as the economy depicted in Figure 3.

B.3 Beyond Two-Period Careers

We now formalize the perpetual-youth extension summarized in Section 5. Following Yaari (1965) and Blanchard (1985), workers die between periods with probability $\zeta \in (0,1)$, and a mass ζ of newborn workers enters each period, keeping the population constant. Workers who enter the modern sector begin their careers as juniors and, conditional on survival, become seniors with probability $\lambda \in (0,1)$ each period. Once senior, a worker remains senior until death.

Workers have an expected lifetime utility:

$$U_t = \sum_{s=t}^{\infty} \left[(1-\zeta) \cdot \beta\right]^{s-t} \cdot u(c_{t,s}),$$

where $c_{t,s}$ is the period-s consumption of a worker born at t and $u(c) = \frac{c^{1-\gamma}}{1-\gamma}$ with $\gamma \geq 0$. Financial markets are frictionless and complete, so workers can fully insure against mortality and experience-accumulation risk.[26] Define

$$q(R) \equiv \frac{1-\zeta}{R} \qquad \text{and} \qquad \kappa(R) \equiv 1 - q(R) \cdot (\beta \cdot R)^{1/\gamma}.$$

Standard consumption-smoothing arguments imply that consumption is proportional to lifetime wealth:

$$c = \kappa(R) \cdot W.$$

The stationary stocks of junior and senior workers per efficiency unit of labor supplied to the modern sector are:

$$J = \frac{\zeta}{1-(1-\zeta)\cdot(1-\lambda)} \qquad \text{and} \qquad S = \frac{(1-\zeta)\cdot\lambda}{\zeta} \cdot J.$$

Consequently:

$$\frac{S}{J} = \frac{(1-\zeta)\cdot\lambda}{\zeta}.$$

Since the stock of seniors no longer equals the stock of juniors, to ensure that there is a positive experience premium, we now assume that $\alpha > \frac{(1-\zeta)\cdot\lambda}{\zeta+(1-\zeta)\cdot\lambda}$.

Let $W^S(R,\chi)$ denote the discounted lifetime labor income of a modern-sector worker who is already senior, and let $W^J(R,\chi)$ denote that of a worker entering the modern sector as a junior. These are given by:

$$W^S(R,\chi) = \frac{w^S}{1-q(R)},$$

and

$$W^J(R,\chi) = \frac{w^J + \frac{q(R)\cdot\lambda}{1-q(R)} \cdot w^S}{1-q(R)\cdot(1-\lambda)}.$$

The corresponding lifetime labor income of a traditional-sector worker is:

$$W^T(R) = \frac{1}{1-q(R)}.$$

Because a type-ψ worker's modern-sector labor income is scaled by ψ, occupational choice is characterized by the cutoff:

$$\bar{\psi} \cdot W^J(R,\chi) = W^T(R). \tag{18}$$

[26] Such insurance can be implemented through annuities and state-contingent borrowing against future labor income.

Workers with $\psi \geq \bar{\psi}$ enter the modern sector, while the rest enter the traditional sector. Equation (18) defines the Labor Market schedule relating $\bar{\psi}$ and R.

To derive the Financial Market schedule, define:

$$\mathcal{W}^M(R,\chi) = J \cdot W^J(R,\chi) + S \cdot W^S(R,\chi)$$

as the lifetime labor-income wealth of the modern-sector workforce per efficiency unit of labor supplied to that sector. Aggregate consumption is

$$C(R,\bar{\psi},\chi) = \kappa(R) \cdot \left[F(\bar{\psi}) \cdot W^T(R) + \int_{\bar{\psi}}^{\infty} \psi dF(\psi) \cdot \mathcal{W}^M(R,\chi) \right].$$

Aggregate output net of automation costs is:

$$Y(\bar{\psi},\chi) = F(\bar{\psi}) + \int_{\bar{\psi}}^{\infty} \psi dF(\psi) \cdot Y^M,$$

where Y^M denotes net output per efficiency unit of labor supplied to the modern sector. Goods-market clearing, $C(R,\bar{\psi},\chi) = Y(\bar{\psi},\chi)$, can be written as:

$$F(\bar{\psi}) \cdot S^T(R) = \int_{\bar{\psi}}^{\infty} \psi dF(\psi) \cdot B^M(R,\chi), \tag{19}$$

where:

$$S^T(R) = 1 - \kappa(R) \cdot W^T(R) = 1 - \frac{\kappa(R)}{1-q(R)}$$

is saving per traditional-sector worker and:

$$B^M(R,\chi) = \kappa(R) \cdot \mathcal{W}^M(R,\chi) - Y^M$$

is borrowing per efficiency unit of labor supplied to the modern sector. Equation (19) defines the Financial Market schedule. The intersection of (18) and (19) determines the stationary-equilibrium pair $(\bar{\psi}^*, R^*)$.

We now characterize the effect of so-so automation. Gross modern-sector production per efficiency unit of labor is $S^\alpha \cdot (J+k)^{1-\alpha}$. Since firms make zero profits after paying for automation, modern-sector output net of automation costs satisfies:

$$Y^M = S^\alpha \cdot (J+k)^{1-\alpha} - \chi \cdot k = J \cdot w^J + S \cdot w^S.$$

Without automation, $k = 0$, and the junior wage equals the marginal product of junior labor. When automation is used, its marginal cost caps that wage. Hence:

$$w^J = \min\left\{\chi, (1-\alpha)\cdot\left(\frac{S}{J}\right)^{\alpha}\right\}.$$

The automation-adoption threshold is therefore:

$$\widehat{\chi} = (1-\alpha)\cdot\left(\frac{S}{J}\right)^{\alpha} = (1-\alpha)\cdot\left(\frac{(1-\zeta)\cdot\lambda}{\zeta}\right)^{\alpha}.$$

Hence, near the threshold, we have:

$$\left.\frac{dw^J}{d\chi}\right|_{\chi=\widehat{\chi}^-} = 1.$$

Moreover, because $w^S = \alpha\cdot\left(\frac{1-\alpha}{w^J}\right)^{\frac{1-\alpha}{\alpha}}$, we have:

$$\left.\frac{dw^S}{d\chi}\right|_{\chi=\widehat{\chi}^-} = -\frac{J}{S}.$$

Thus, a decline in χ lowers the junior wage and raises the senior wage, making modern-sector labor income more backloaded. At the same time,

$$dY^M = J\cdot dw^J + S\cdot dw^S = 0.$$

Marginal automation therefore rotates the modern-sector wage profile without changing net output per efficiency unit of modern-sector labor.

Consider first the Labor Market schedule. Holding R fixed and differentiating $W^J(R,\chi)$ near the adoption threshold (from below) yields:

$$\frac{\partial W^J(R,\chi)}{\partial\chi} = \frac{1-\frac{q(R)\cdot\lambda}{1-q(R)}\cdot\frac{J}{S}}{1-q(R)\cdot(1-\lambda)} = \frac{\frac{R-1}{R-(1-\zeta)}}{1-\frac{1-\zeta}{R}\cdot(1-\lambda)} > 0,$$

where the inequality follows from the fact that $R > 1$ in any stationary equilibrium.[27] A decline in χ therefore reduces the discounted lifetime labor income of a worker entering the modern sector as a junior. By equation (18), the modern-sector career becomes less attractive and the Labor Market schedule shifts to the

[27]The gross interest rate exceeds one because workers discount future consumption and modern-sector labor income is backloaded.

right.

Next, consider the Financial Market schedule. Differentiating aggregate modern-sector lifetime wealth near the adoption threshold (from below) yields:

$$\frac{\partial \mathcal{W}^M(R,\chi)}{\partial \chi} = -\frac{J \cdot q(R) \cdot \lambda \left(1 + \frac{J}{S}\right)}{[1 - q(R)] \cdot [1 - q(R) \cdot (1 - \lambda)]} < 0.$$

Thus, a decline in χ raises the lifetime labor-income wealth, and thus desired consumption, of the existing modern-sector workforce. Since marginal automation leaves current modern-sector output unchanged,

$$\frac{\partial B^M(R,\chi)}{\partial \chi} = \kappa(R) \cdot \frac{\partial \mathcal{W}^M(R,\chi)}{\partial \chi} < 0.$$

A decline in χ therefore raises borrowing demand per efficiency unit of modern-sector labor. For a given interest rate, financial-market clearing requires fewer modern-sector borrowers and more traditional-sector savers, so the Financial Market schedule also shifts to the right.

Both equilibrium schedules consequently shift to the right following a marginal decline in χ below the adoption threshold, raising the equilibrium cutoff $\bar{\psi}^*$. Because so-so automation has no first-order effect on modern-sector net output per worker, its only first-order output effect operates through the reallocation of workers across sectors. The modern sector must compensate workers for its backloaded wage profile and is therefore more productive at the occupational margin, so that $\bar{\psi}^* \cdot Y^M > 1$. The increase in $\bar{\psi}^*$ reallocates workers away from the modern sector and lowers aggregate output. So-so automation thus remains immiserizing when workers have longer careers and accumulate experience gradually.

B.4 Direct Path to Senior Occupations

Our baseline model assumes that workers must accumulate experience in junior tasks before they can perform senior tasks. One might conjecture that relaxing this assumption weakens the immiseration mechanism. If workers displaced from junior tasks can enter senior occupations directly, they need not leave the modern sector when automation reduces the return to apprenticeship. This intuition is incomplete.

Direct entry provides workers with a flatter earnings profile than apprenticeship, but does so by sacrificing the productivity gains from experience accumulation. As automation increasingly backloads apprenticeship earnings, workers may therefore become willing to sacrifice average earnings in exchange for the flatter earnings profile offered by direct entry. The same force that drives workers toward the traditional sector in our baseline model can thus also generate a reallocation within the modern sector, potentially amplifying rather than attenuating immiseration.

To formalize this idea, suppose that a young worker of type ψ who enters senior tasks directly supplies $\kappa_1 \cdot \psi$ efficiency units of senior labor when young and $\kappa_2 \cdot \psi$ efficiency units when old, where:[28]

$$0 < \kappa_1 \leq \kappa_2 < 1.$$

The restriction $\kappa_2 < 1$ captures the productivity cost of bypassing apprenticeship: workers who enter senior occupations directly never become as productive as workers who first accumulate experience in junior tasks.

Workers can now choose among three career paths:

$$D : (\psi \cdot \kappa_1 \cdot w^S, \psi \cdot \kappa_2 \cdot w^S), \qquad A : (\psi \cdot w^J, \psi \cdot w^S), \qquad T : (1, 1),$$

where D denotes direct entry into the modern-sector senior occupation, A denotes "apprenticeship" in the modern sector, and T denotes a traditional-sector career. Workers rank occupational paths by discounted lifetime labor income. Direct entry is weakly preferred to apprenticeship whenever:

$$\kappa_1 \cdot w^S + \frac{\kappa_2 \cdot w^S}{R} \geq w^J + \frac{w^S}{R}. \tag{20}$$

We focus on parameters such that this condition fails before automation. Apprenticeship is then initially the preferred route through the modern sector. As junior-task automation reduces w^J and raises w^S, apprenticeship becomes increasingly backloaded, and direct entry eventually becomes attractive.

At the point of indifference between the two modern-sector paths:

$$\kappa_1 \cdot w^S - w^J = \frac{(1 - \kappa_2) \cdot w^S}{R} > 0.$$

[28] An old worker who has worked in the traditional sector when young is assumed to supply $\kappa_1 \cdot \psi$ efficiency units when entering the modern sector.

Thus, direct entry pays more when young and less when old, providing a flatter earnings profile. Moreover, because $R > 1$ in any equilibrium, equality of discounted lifetime earnings implies:

$$(\kappa_1 + \kappa_2) \cdot w^S < w^J + w^S.$$

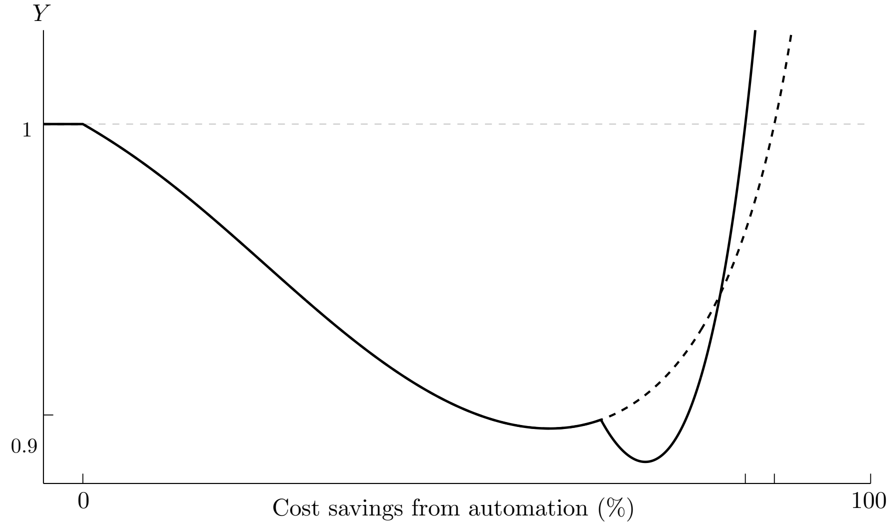
Workers are therefore willing to accept lower average earnings in exchange for a flatter earnings profile. Since competitive wages equal marginal products, this reallocation also lowers their contribution to aggregate output.

The logic parallels the reallocation toward the traditional sector in our baseline model. There, workers respond to the backloading induced by junior-task automation by leaving the modern sector, sacrificing higher average marginal products for the flatter earnings profile available in the traditional sector. Here, the same force operates additionally within the modern sector: workers can bypass apprenticeship and sacrifice the productivity gains from experience accumulation in exchange for the flatter earnings profile offered by direct entry. Allowing an alternative path into senior occupations can therefore amplify, rather than attenuate, immiseration.

Figure B.2 illustrates this amplification. The dashed line reproduces the baseline economy, while the solid line allows for direct entry into senior occupations. For sufficiently small cost savings, direct entry is unattractive and the two economies coincide. As automation becomes more productive and apprenticeship earnings become increasingly backloaded, workers begin to switch toward direct entry. By reducing experience accumulation, this additional reallocation deepens the decline in output relative to the baseline. Eventually, as automation becomes sufficiently productive, its direct productivity gains dominate both reallocation effects and output recovers.

We next characterize the equilibrium underlying Figure B.2. Because all modern-sector entrants rank apprenticeship and direct entry in the same way, a strict preference for either path would lead all of them to choose it. The economy can thus feature three regimes as automation becomes more productive: an apprenticeship-only regime, an intermediate regime where apprenticeship and direct entry coexist, and a direct-entry-only regime. We begin with the intermediate regime, which generates the additional reallocation margin highlighted above.

Figure B.2: Immiseration Under Expanded Career Paths



Notes: This figure depicts output relative to its pre-automation level as a function of cost savings from automation $1-\chi/(1-\alpha)$, with the direct-entry path ($\kappa_1=\kappa_2=1/4$) shown by the solid line and the baseline model without direct entry shown by the dashed line. Both economies are governed by the same preference and technological parameters as the economy depicted in Figure 3.

The tie between apprenticeship and direct entry pins down the interest rate:

$$R_{AD}=\frac{1-\kappa_2}{\kappa_1-\frac{w^J}{w^S}}.$$

At this interest rate, apprenticeship and direct entry share the same cutoff against traditional work:

$$\bar{\psi}_{AD}=\frac{1+1/R_{AD}}{w^J+w^S/R_{AD}}=\frac{1+1/R_{AD}}{\kappa_1\cdot w^S+\kappa_2\cdot w^S/R_{AD}}.$$

Let $m\in[0,1]$ denote the fraction of modern entrants choosing apprenticeship. Financial market clearing in the mixed regime implies:

$$\begin{aligned}F(\bar{\psi}_{AD})\cdot\left[1-\omega(R_{AD})\cdot\left(1+\frac{1}{R_{AD}}\right)\right]\\ =\int_{\bar{\psi}_{AD}}^{\infty}\psi dF(\psi)\cdot\Bigg\{m\cdot\left[\omega(R_{AD})\cdot\left(w^J+\frac{w^S}{R_{AD}}\right)-w^J\right]\\ +(1-m)\cdot\left[\omega(R_{AD})\cdot\left(\kappa_1\cdot w^S+\frac{\kappa_2\cdot w^S}{R_{AD}}\right)-\kappa_1\cdot w^S\right]\Bigg\}.\end{aligned}$$

This equation determines the apprenticeship share m. The mixed regime is valid when the implied value of m lies in $[0, 1]$. If the implied value exceeds one, the apprenticeship-only regime is the relevant candidate; if it is negative, the direct-entry-only regime is the relevant candidate.

In the apprenticeship-only regime, condition (20) fails at the equilibrium interest rate and the baseline Labor Market and Financial Market conditions apply. In the direct-entry-only regime, the cutoff against traditional work is:

$$\bar{\psi}_D = \frac{1 + 1/R}{\kappa_1 \cdot w^S + \kappa_2 \cdot w^S/R}.$$

The interest rate is determined by:

$$\begin{aligned} F(\bar{\psi}_D) \cdot \left[1 - \omega(R) \cdot \left(1 + \frac{1}{R}\right)\right] \\ = \int_{\bar{\psi}_D}^{\infty} \psi dF(\psi) \cdot \left[\omega(R) \cdot \left(\kappa_1 \cdot w^S + \frac{\kappa_2 \cdot w^S}{R}\right) - \kappa_1 \cdot w^S\right], \end{aligned}$$

together with the requirement that condition (20) holds at the resulting interest rate.

Lastly, no worker would choose a career path that involves working in the traditional sector when young and in the modern sector when old. To see this, let $\bar{\psi}$ denote the cutoff between traditional work in both periods and the preferred modern-sector path, i.e., the better of apprenticeship and direct entry. At this cutoff, $\bar{\psi} \cdot \kappa_1 \cdot w^S \leq 1$; otherwise, since $\kappa_2 \geq \kappa_1$, direct entry in both periods would strictly dominate traditional work. For $\psi < \bar{\psi}$, the hybrid path has the same young income as traditional work and lower old income, so traditional work dominates it. For $\psi > \bar{\psi}$, multiply the income profile of the traditional path at the cutoff by $\psi/\bar{\psi}$. Since modern-sector earnings scale proportionally with ψ, the preferred modern-sector path dominates this scaled traditional profile. The latter, in turn, dominates the hybrid path: its young income is strictly above one and, because $\bar{\psi} \cdot \kappa_1 \cdot w^S \leq 1$, its old income is at least $\psi \cdot \kappa_1 \cdot w^S$. Thus, the hybrid path is never chosen in equilibrium.

For completeness, below we provide the equations that characterize stationary equilibrium output underlying Figure B.2. Production in the apprenticeship-only regime is:

$$J_A = S_A = \int_{\bar{\psi}}^{\infty} \psi dF(\psi).$$

In the mixed regime:

$$J_{AD} = m \cdot \int_{\bar{\psi}_{AD}}^{\infty} \psi \, dF(\psi), \qquad S_{AD} = \left[m + (1-m) \cdot (\kappa_1 + \kappa_2)\right] \cdot \int_{\bar{\psi}_{AD}}^{\infty} \psi \, dF(\psi).$$

In the direct-entry-only regime:

$$J_D = 0, \qquad S_D = (\kappa_1 + \kappa_2) \cdot \int_{\bar{\psi}_D}^{\infty} \psi \, dF(\psi).$$

Factor prices satisfy the usual competitive conditions:

$$w^J = (1-\alpha) \cdot \left(\frac{S}{J+k}\right)^{\alpha} \leq \chi, \qquad w^S = \alpha \cdot \left(\frac{J+k}{S}\right)^{1-\alpha},$$

with equality $w^J = \chi$ whenever automation is used. Since firms make zero profits, stationary net output equals total labor income. Thus, in the mixed regime:

$$Y_{AD} = 2 \cdot F(\bar{\psi}_{AD}) + \int_{\bar{\psi}_{AD}}^{\infty} \psi dF(\psi) \cdot \left[m \cdot (w^J + w^S) + (1-m) \cdot (\kappa_1 + \kappa_2) \cdot w^S\right],$$

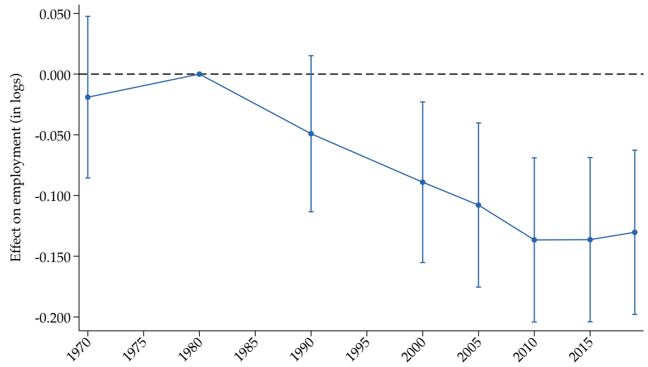
while in the direct-entry-only regime:

$$Y_D = 2 \cdot F(\bar{\psi}_D) + (\kappa_1 + \kappa_2) \cdot w^S \cdot \int_{\bar{\psi}_D}^{\infty} \psi dF(\psi).$$

The apprenticeship-only output expression is the same as in our baseline model.

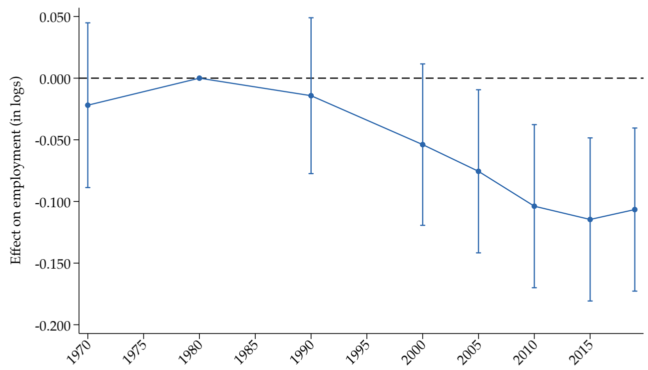
C Empirical Evidence: Additional Figures

Figure C.1: Employment Effects of Junior Bias in Robot Exposure When Using an Alternative Measure of Junior Bias



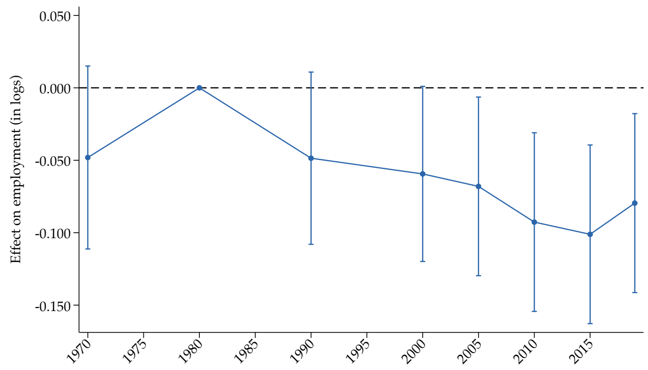
Notes: This figure reports estimates of the parameters $\beta_{t'}$ in equation (7). The dependent variable is an industry's log employment. In contrast to the baseline, junior bias is here defined as the difference between the exposure of workers who are younger vs. older than the industry-specific median age. The coefficients are normalized by the standard deviation of the independent variable so that they reflect effects per standard deviation of junior bias. The regression controls for year and industry fixed effects and for the overall exposure of the industry to automation by robots, interacted with year. The bars reflect 90% confidence intervals.

Figure C.2: Employment Effects of Junior Bias in Robot Exposure When Using an Alternative Occupational Exposure Measure



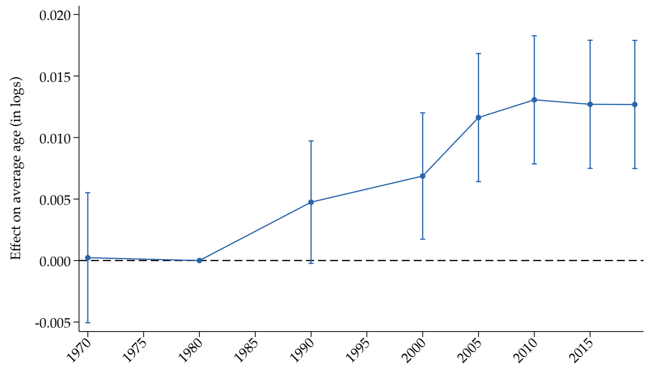
Notes: This figure reports estimates of the parameters $\beta_{t'}$ in equation (7). The dependent variable is an industry's log employment. These estimates rely on exposure measures constructed by Webb (2019) rather than those by Garg et al. (2026) as in the baseline. The coefficients are normalized by the standard deviation of the independent variable so that they reflect effects per standard deviation of junior bias. The regression controls for year and industry fixed effects and for the overall exposure of the industry to automation by robots, interacted with year. The bars reflect 90% confidence intervals.

Figure C.3: Employment Effects of Junior Bias in Robot Exposure When Computing Exposure Based on the 1990 Census



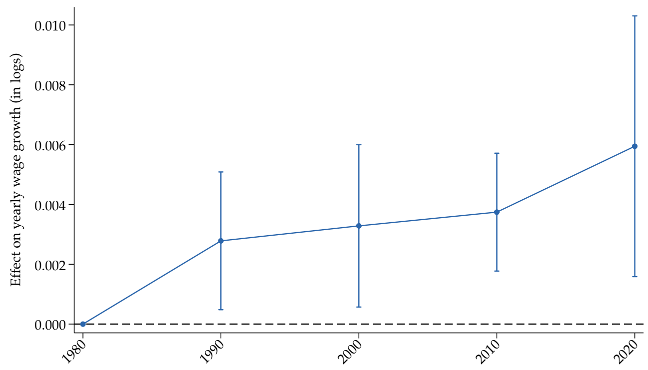
Notes: This figure reports estimates of the parameters $\beta_{t'}$ in equation (7). The dependent variable is an industry's log employment. Exposure to automation and the junior bias in automation are computed based on data in the 1990 Census rather than the 1980 Census in the baseline. The coefficients are normalized by the standard deviation of the independent variable so that they reflect effects per standard deviation of junior bias. The regression controls for year and industry fixed effects and for the overall exposure of the industry to automation by robots, interacted with year. The bars reflect 90% confidence intervals.

Figure C.4: Age Effects of Junior Bias in Automation Exposure



Notes: This figure reports estimates of the parameters $\beta_{t'}$ in equation (7). The dependent variable is an industry's log average age. The coefficients are normalized by the standard deviation of the independent variable, so that they reflect effects per standard deviation of junior bias. The regressions control for year and industry fixed effects and for the overall exposure of the industry to automation, interacted with year. The bars reflect 90% confidence intervals.

Figure C.5: Wage Backloading Effects of Junior Bias in Automation Exposure



Notes: This figure reports estimates of the correlation between the junior bias in automation and the wage growth of workers employed in that industry. The dependent variable is an individual worker's log wage growth. The coefficients are normalized by the standard deviation of the independent variable, so that they reflect effects per standard deviation of junior bias. The regressions control for time (year and month), sex, age and industry fixed effects and for the overall exposure of the industry to automation, interacted with year. Standard errors are clustered at the industry level. The bars reflect 90% confidence intervals.