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Abstract

We argue that because the US system is distorted against labor and in favor of capital and has become more so in recent times, it has promoted levels of automation beyond what is socially desirable. Moving from the US tax system and level of automation in the 2010s to optimal taxation of factors and corresponding optimal level of automation would raise employment by 5.85% and the labor share by 0.53 percentage points. If moving to optimal policy is not feasible, more modest reforms can still increase employment by 1.35-2.31%. Interestingly, if only partial reforms are feasible, our theoretical framework and quantitative work show that it would not be desirable to increase taxation of capital per se (even though capital is lightly taxed in the US); rather, directly reducing the extent of automation would be much more effective. This is because marginal automated tasks do not bring much productivity gains and displace workers, reducing employment. In contrast, increasing the capital intensity of already-automated tasks raises the demand for labor because of the complementarity between tasks. These conclusions are reinforced when technology and/or human capital investments are endogenous and respond to tax policies.

Keywords: automation, capital, employment, labor share, optimal taxes, tasks, taxation.

JEL Classification: J23, J24.

Conference Draft. Still in Progress.

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1 Introduction

The last three decades have witnessed a declining share of labor in national income, stagnant median real wages and lower real wages for low-skill workers in the US economy (Elsby, Hobijn & Sahin, 2011; Acemoglu & Autor, 2011; Karabarbounis & Neiman, 2014). The labor share in non-farm private businesses, for example, declined from 63.6% in 1980 to 56.6% in 2017, while median real wages grew only by 16% (as compared to GDP per capita which doubled during the same period) and the real wages of male workers with a high school diploma fell by 6% between 1980 and 2017. In the meantime, the production process has become increasingly more automated, as computerized numerical control machines, industrial robotics, specialized software and lately artificial intelligence technologies have spread rapidly throughout the economy. For instance, the US economy had a total of 2.5 industrial robots per thousand workers in manufacturing in 1993 and this number rose to 20 by 2019 (Acemoglu & Restrepo, 2020a). From a base of essentially zero in the mid-2000s, the share of vacancies posted for artificial intelligence-related activities increased to 0.75% by 2018 (Acemoglu et al., 2020).

Many see a close connection between the growing trend towards automation and some of the aforementioned adverse labor market developments (Acemoglu and Autor, 2011; Brynjolfsson & McAfee, 2014; Ford, 2015; Autor & Salomons, 2019). Acemoglu & Restrepo (2019a), for example, show that there has been more rapid displacement of workers due to automation during the last three decades than before, and Acemoglu & Restrepo (2020b) provide evidence that this trend has contributed to increasing inequality.

The most common perspective among economists is that even if automation is contributing to declining labor share and stagnant wages, the adoption of these new technologies is likely to be beneficial, and any adverse consequences thereof should be dealt with appropriate redistributive policies (and education and training investments). But could it be that the extent of automation is excessive, meaning that US businesses are adopting automation technologies beyond the socially optimal level? If this were the case, the policy responses to these major labor market trends would need to be rethought.

There are several reasons why the level of automation may be excessive. Perhaps most saliently, the US tax system is known to tax capital lightly and provide various subsidies to the use of capital in businesses (CBO, 2014; Barro & Furman, 2019).[1] In this paper, we systematically document the asymmetric taxation of capital and labor in the US economy

[1] Another set of reasons for excessive automation are related to different types of labor market imperfections and are investigated in our companion paper, Acemoglu, Manera & Restrepo (2020), and we discuss these ideas briefly later in the paper.

and investigate whether it can lead to excessive development and adoption of automation technologies, and if so, what policy levers would be most useful to combat this tendency.

We start with a task-based model of automation, building on Acemoglu & Restrepo (2018, 2019a,b) and Zeira (1998). We enrich this framework by introducing a reduced-form labor market imperfection. We then analyze optimal capital and labor taxes and automation decisions in this environment.[2] Our first theoretical result establishes that, without additional constraints on policy, optimal capital and labor taxes are tightly linked to the elasticities of supply of these factors, and once these taxes are set optimally, the planner has no reason to distort equilibrium automation decisions. Intuitively, optimal taxes undo any distortions and ensure that market prices reflect the social values of capital and labor. Automation decisions that take these prices as given are therefore optimal.

Yet this result does not imply that equilibrium automation decisions are optimal at arbitrary capital and labor taxes. In particular, our second theoretical result shows that if a tax system is biased against labor and in favor of capital, then reducing automation at the margin is welfare improving. This is because reducing automation starting from its equilibrium level has a second-order cost, which is related to the fact that productivity gains from automation at marginal tasks are small (or, equivalently, the automation of these marginal tasks corresponds to "so-so automation" in the terminology of Acemoglu & Restrepo, 2019a). But it has a first-order benefit because automation creates a displacement effect as it replaces labor with machines (Acemoglu & Restrepo, 2018, 2019a). When the tax system is biased against labor, the level of employment is necessarily too low relative to the social optimum, and the displacement created by automation has a negative impact on welfare. Consequently, reducing automation enables socially beneficial increases in employment.

A common intuition is that if taxes are distorted, then the best policy remedy is to correct these distortions. Hence, if a tax system treats capital too favorably, we should directly tackle this distortion and increase capital taxes. We demonstrate that this intuition does not always apply in the presence of other constraints. In particular, in the context of automation, a tax system distorted in favor of capital may call for reducing equilibrium automation even if raising capital taxes is possible. This is because of the tight link between welfare and the level of employment in the presence of a tax system that is biased against labor. Because capital and labor are $q-$complements, increasing the capital stock of the economy tends to raise employment (Acemoglu & Restrepo, 2019a,b). Thus, rather than reducing the capital intensity of tasks that are (and should be) automated, it is more beneficial to reduce the

[2] For simplicity, we do this in a static economy in the text. We generalize our main results to a dynamic economy in the Appendix.

extent of automation at the margin, which then avoids the displacement of workers from these marginal tasks and tends to push up employment. This result reiterates the importance of distinguishing between the choice of capital intensity in a task and the *extensive margin* of automation (i.e., which tasks are allocated to capital).

Armed with these results, we turn to an investigation of optimal capital and labor taxes in the US economy and their comparison to the actual tax system. Using plausible ranges of labor and capital elasticities and parameterizations of labor market distortions, we find that optimal labor taxes are lower than capital taxes. Specifically, our baseline numbers suggest that capital should be taxed at 27%, while labor should be taxed at 16%. Optimal taxes are higher on capital than labor because empirically plausible ranges of supply elasticities for capital and labor are similar, but employment decisions are further distorted by labor market imperfections. In contrast to this optimal benchmark, in the US tax system labor is much more heavily taxed than capital. Mapping the complex range of taxes in the US to effective capital and labor taxes is not trivial. Nevertheless, under plausible scenarios (for example, depending on how much of healthcare and pension expenditures are valued by workers and the effects of means-tested benefits), we find that labor taxes in the US are in the range of 25.5-33.5%. Effective capital taxes on software and equipment, on the other hand, are much lower, about 10% in the 2010s and even lower, about 5%, after the 2017 tax reforms. We also show that effective taxes on software and equipment have experienced a sizable decline from a peak value of 20% in the year 2000.[3] A major reason explaining this trend in capital taxation is the increased generosity depreciation allowances, which we document in detail.

Most importantly for our focus, we find that the US tax system favors excessive automation. In particular, the heavy taxation of labor and low taxes on capital encourage firms to automate more tasks and use less labor than is socially optimal. Our computations suggest that moving from the current tax system to optimal taxes would increase employment by 5.85% and the labor share by 0.53 percentage points.[4] This can be achieved via an *automation tax*—a higher tax on the use of capital in tasks where labor has a comparative advantage. An automation tax encourages the use of capital at tasks in which capital has a comparative advantage and discourages the automation of marginal tasks. A 12.85% automation tax

[3] Acemoglu & Restrepo (2019a) document that technological changes in the four decades after World War II involved less automation and more of technologies that increased human productivity (such as the creation of new tasks for workers) than recently. Though there are other reasons for why the direction of technology changed, the lower taxation of equipment and software capital may have been one of the important factors.

[4] Despite these large changes in employment, the increase in welfare, given by a "Harberger triangle", is as usual smaller — 0.61% in consumption-equivalent terms. For instance, Harberger (1954) estimated consumption-equivalent welfare gains from removing monopoly distortions across sectors of 0.1% and Lucas (1987) estimated welfare gains from eliminating business cycles of less than 0.01% (Atkeson & Phelan, 1994, estimated even smaller gains with incomplete markets).

would by itself raise employment by 1.35% and the labor share by 2.06 percentage points. An automation tax improves welfare because the automation of marginal tasks has a small impact on productivity but imposes a first-order welfare cost on displaced workers (recall that employment is suboptimally low given the bias of the tax system against labor).

Furthermore, echoing our theoretical discussion above, we find that it would be more beneficial to reduce automation while at the same time increasing the capital intensity of infra-marginal automated tasks. For instance, a 15.62% automation tax combined with a *reduction* in overall capital taxes from 10% to 8.89% would have a larger impact—increasing employment by 1.75% and the labor share by 2.51 percentage points.

We further document that a number of realistic extensions of our framework reinforce these conclusions. For example, if human capital is endogenous, the asymmetric treatment of capital and labor becomes more costly because it also distorts human capital investments, and in this case, our policy conclusions are strengthened (that is, the estimated optimal taxes are even further away from the current tax system). The same is true when the development of automation technologies is modeled (albeit in a reduced-form manner in this paper) and there is a trade-off between automation and the creation of new tasks that directly increase the marginal product of labor. In this latter case, we also show that it may be optimal to redirect technological efforts from automation because excessive adoption of automation technologies is being fed by the development of excessively automated technologies.

Our paper is related to several classic and recent literatures, though, to the best of our knowledge, no other paper investigates whether the US tax system is encouraging excessive automation.

First, there is an emerging literature on taxation of robots and automation (Guerreiro, Rebelo & Teles, 2017; Thuemmel, 2018; Costinot & Werning, 2018, and Tsyvinski & Werquin, 2019). This literature studies whether adverse distributional effects of automation call for taxes or distortions on automation technologies in a setting where redistribution can only be achieved though income taxes. Our paper is complementary to this literature. It abstracts from distributional concerns and instead turns to a different aspect of the problem of optimal automation—the question of whether automation should be taxed in order to improve productivity and welfare. In particular, we focus on situations in which the tax system is biased against labor (which, as we document, is a feature of the US tax system) and, because of labor market imperfections, the key policy objective is to raise employment (not to redistribute income).

Second, our paper is related to the literature on optimal capital and labor taxation (e.g., Atkinson & Stiglitz, 1972, Judd, 1985, Chamley 1986, and Straub & Werning, 2020). Much of this literature focuses on dynamic models, while our benchmark is a static setting where optimal taxes are related to supply elasticities and distortions in the labor market. Although dynamic optimal taxes also depend on the anticipation of future prices and taxation, our main insights generalize to a dynamic environment. In particular, as shown by Straub & Werning (2020), when the long-run elasticity of capital supply is not infinite, capital taxes should converge to zero in the long run only if labor taxes converge to zero as well. Hence, even in a dynamic setting, uniform taxation of capital and labor in the long run may be optimal under plausible conditions. We also show that in the presence of labor market distortions the long-run tax rate on labor should be lower than the tax rate on capital, and under reasonable assumptions, the same elasticities also govern optimal capital and labor taxes in the long run.

Third, our paper relates to the literature on the effects of tax reforms on investment and labor market outcomes. A branch of this literature estimates the differential responses of investment in firms facing different taxes (Cummins, Hassett & Hubbard, 1994; Goolsbee, 1998; Hasset & Hubbard, 2002; Desai & Goolsbee, 2004; Edgerton, 2010; Yagan, 2015). Modal results in this literature find investment elasticities with respect to the keep rate (one minus tax rate) that range between 0.5 and 1.[5] Importantly, however, this literature focuses on firms' demand for capital, while what is relevant in our setting is the (long-run) elasticity of the supply of capital. This elasticity depends on how much the marginal cost of producing investment goods increases with investment (which it will do so long as the non-substitution theorem does not apply) and on how an increase in savings affects intertemporal substitution. We discuss estimates of this elasticity based on the response of the supply of capital to wealth and capital income taxes below (see Kleven & Schultz, 2014; Zoutman, 2018; Brülhart et al., 2019; Jakobsen et al., 2019; Duran-Cabré et al., 2019).

Fourth, even more closely connected to our work is the literature on the labor market implications of tax reforms. Suárez Serrato & Zidar (2016) exploit the incidence of tax changes across US counties and estimate that a 1% increase in the keep rate of corporate taxes raises employment by 3.5% and wages by 0.8%, and that workers bear 35% of the incidence. These estimates suggest a fairly elastic response of employment and a less than perfectly elastic response of capital at the local-labor market level (a perfectly elastic response of capital would cause workers to bear the full incidence). Likewise, Garret, Ohrn & Suárez Serrato (2020) compare counties at the 75th percentile of exposure to bonus depreciation allowances to those at the 25th percentile and find a 2% increase in employment, no changes

[5] More recent work by House & Shapiro (2008) documents a large investment response and argue that this was due to the temporary nature of the bonus, while Zwick & Mahon (2017) estimate investment elasticities with respect to the keep rate that are around 1.5 for most firms, though larger for smaller firms.

in wages, and a 3.3% increase in investment in response to the reform.

Finally, our modeling of automation builds on various other papers in the labor and macroeconomics literatures, such as Zeira (1998), Autor, Levy & Murnane (2003), Acemoglu & Autor (2011) and most closely, Acemoglu & Restrepo (2018, 2019a,b). The task-based framework is particularly useful in our setting because it shows how automation (substituting capital for labor in tasks previously performed by humans) creates a displacement effect while automating marginal tasks generates limited productivity gains (because firms are approximately indifferent between automating these tasks or producing with labor). This combination of displacement effects and small productivity gains is at the root of our most important results—that the planner would like to reduce automation at the margin when the tax system is biased against labor. This framework also clarifies how policy can affect the level of automation and why this is different from taxing capital (this is highlighted, in particular, by our result that it may be optimal to reduce automation while simultaneously increasing capital intensity in automated tasks).

The rest of the paper is organized as follows. Section 2 introduces our conceptual framework and derives optimal tax and automation levels without constraints on capital and labor taxation, and also provides conditions for excessive automation under arbitrary tax schedules and in the presence of further constraints. Our analysis in this section uses a static model for ease of exposition; dynamic generalizations are presented in the Appendix. Section 3 provides a detailed discussion of the US tax system and maps the complex US tax code into effective capital and labor income taxes. Section 4 estimates optimal taxes using plausible ranges of elasticities of capital and labor supplies and labor market distortions, and compares these to US taxes derived in Section 3. We consider several extensions in Section 5. Section 6 concludes, while the Appendix contains proofs of the results stated in the text, various theoretical generalizations, and further details for and robustness checks on our computations for the US tax system.

2 Conceptual Framework

In this section we present our conceptual framework for evaluating the optimality of capital and labor taxes and the extent of automation. To communicate the main ideas in the most transparent fashion, we focus on a static model. Results on optimal dynamic taxes are presented in the Appendix.

2.1 Environment

There is a unique final good, produced by combining a unit measure of tasks,

$$y = \left(\int_0^1 y(x)^{\frac{\lambda-1}{\lambda}} dx \right)^{\frac{\lambda}{\lambda-1}}.$$

As in Zeira (1998), Acemoglu & Autor (2011) and Acemoglu & Restrepo (2018, 2019a,b), tasks are allocated between capital and labor, and performed with the following task-level production function:

$$y(x) = \psi^\ell(x) \cdot \ell(x) + \psi^k(x) \cdot k(x), \tag{1}$$

where $\ell(x)$ is labor employed in task x, $k(x)$ is the amount of capital of type x (used in the production of task x), and $\psi^\ell(x)$ and $\psi^k(x)$ denote, respectively, the productivities of labor and capital in task x. We order tasks such that $\psi^\ell(x)/\psi^k(x)$ is nondecreasing and simplify the exposition by assuming that it is strictly increasing. We also suppose that when indifferent between producing a task with capital or labor, firms produce with capital. Therefore, there exists a threshold task θ such that tasks in $[0, \theta]$ are produced with capital and tasks in $(\theta, 1]$ are produced with labor. For now, there is no distinction between the adoption of automation technologies and the development of such technologies, but we introduce this distinction and explore its implications in Section 5.2.

Capital used in each task is produced from the final good with a convex cost $\phi(k)$, where $k = \int_0^1 k(x)dx$ is the total amount of capital in the economy.[6]

The household side is inhabited by a representative household who obtains utility

$$u(c, \ell) = c - \nu(\ell),$$

from consuming c units of output and supplying ℓ units of labor. Here ν is a convex function representing the disutility from working.

To ensure uniqueness we assume that $\phi'(k) \cdot k$ and $\nu'(\ell) \cdot \ell$ are convex. Finally, we denote the capital supply elasticity by $\varepsilon^k(k) = \phi'(k)/(\phi''(k) \cdot k)$ and the (Hicksian) elasticity of labor supply by $\varepsilon^\ell(\ell) = \nu'(k)/(\nu''(\ell) \cdot \ell)$.

Firms rent labor and capital at prices w and R. Capital and labor are taxed at constant

[6] The function $\phi(k)$ stands in for a range of considerations making the aggregate supply of capital less than perfectly elastic. Most importantly, the marginal rate of intertemporal substitution of households between current and future consumption can change as a function of their wealth (which we explore in detail in the Appendix).

(linear) tax rates τ^k and τ^ℓ, respectively. After-tax prices faced by the representative household are therefore $w \cdot (1-\tau^\ell)$ and $R \cdot (1-\tau^k)$. Tax revenues are used for financing a fixed level of government expenditure, denoted by g.

We allow for various types of frictions in the labor market, which can be modeled as introducing a wedge between the market wage and the representative household's marginal cost of supplying labor. We denote this wedge by $\varrho \geq 0$.[7]

2.2 Equilibrium

Given taxes (τ^k, τ^ℓ) and the labor wedge ϱ, a market equilibrium is defined by factor prices (w, R), a tuple of output, consumption, capital and labor, $\{y, c, k, \ell\}$, and an allocation of tasks to factors, such that this allocation minimizes the after-tax cost of producing each task and the markets for capital, labor and the final good clear. The equilibrium level of output can be represented as (see the Appendix):

$$(2) \qquad y = f(k, \ell; \theta) = \left(\left(\int_0^\theta \psi^k(x)^{\lambda-1} dx \right)^{\frac{1}{\lambda}} \cdot k^{\frac{\lambda-1}{\lambda}} + \left(\int_\theta^1 \psi^\ell(x)^{\lambda-1} dx \right)^{\frac{1}{\lambda}} \cdot \ell^{\frac{\lambda-1}{\lambda}} \right)^{\frac{\lambda}{\lambda-1}},$$

where the threshold task θ satisfies

$$(3) \qquad \theta = \theta^m(k, \ell) \equiv \arg\max_{\theta \in [0,1]} f(k, \ell; \theta).$$

Moreover, factor prices are given by the usual marginal conditions $f_k = R$ and $f_\ell = w$. Consequently, the market clearing condition for capital can be written as

$$(4) \qquad \phi'(k) = f_k \cdot (1 - \tau^k),$$

while the market clearing condition for labor is

$$(5) \qquad \nu'(\ell) = f_\ell \cdot (1 - \varrho) \cdot (1 - \tau^\ell).$$

This equation shows that the wedge ϱ and the labor tax τ^ℓ distort the labor supply decision of the representative household in similar ways.

[7] As shown in Acemoglu, Manera & Restrepo (2020), this wedge can be derived from bargaining between workers and firms or from efficiency wage considerations. In that paper, we also allow for such wages to differ across tasks and show that this generates an additional reason for excessive automation. We discuss capital wedges in Section 4.5.

Finally, the government budget constraint takes the form

$$g \leq \tau^k \cdot f_k \cdot k + \tau^\ell \cdot f_\ell \cdot \ell. \tag{6}$$

A couple of points about this equilibrium are worth noting. As emphasized in Acemoglu & Restrepo (2018, 2019a), though the output level in the economy can be represented by a constant elasticity of substitution (CES) aggregate of capital and labor, the implications of this setup are very different from models that assume a CES production function with factor-augmenting technologies. First, there is a crucial distinction between capital intensity of production given a fixed allocation of tasks to factors and the substitution of capital for tasks previously performed by labor—automation, represented by an increase in θ. This can be seen from the fact that holding the task allocation constant, the elasticity of substitution between capital and labor is λ, but when θ adjusts, the elasticity is greater. Second, technological advances that enable further automation possible increase productivity but can easily reduce labor demand and the equilibrium wage because of the displacement created by automation (mathematically, this works by changing the share parameters of the CES). In contrast, labor demand always increases when capital becomes more productive in a standard CES production function. Third, and for the same reason, automation always reduces the labor share. Finally, marginal increases in automation have second-order effects on aggregate output (because of (3)).

2.3 Optimal Policy

We now characterize the optimal policy in this economy by considering the choices of a benevolent social planner that can choose capital and labor taxes τ^k and τ^ℓ subject to the market equilibrium and can also directly control the extent of automation, represented by θ. We refer to the maximization problem of this social planner as the *Ramsey problem*. As usual, this problem can be transformed so that the social planner chooses directly an allocation represented by $\{y, c, k, \ell, \theta\}$ that maximizes household utility subject to the resource constraint of the economy and a single *Implementability Condition*, which combines the government budget constraint in (6), and input market equilibrium conditions (4) and

(5). Namely, the Ramsey problem takes the form

$$
\begin{aligned}
(7) \qquad & \max_{c,\ell,k,\theta} \quad u(c,\ell) \\
\text{subject to:} \quad & c + g = f(k,\ell;\theta) - \phi(k) && \text{(Resource constraint)} \\
& g \leq f(k,\ell;\theta) - \phi'(k)\cdot k - \frac{\nu'(\ell)\cdot\ell}{1-\varrho} && \text{(Implementation Constraint)}
\end{aligned}
$$

Because the planner is assumed to choose the level of automation θ, we do not impose $\theta = \theta^m(k,\ell)$ as an additional constraint. We discuss issues of how the planner's choice of level of automation can be implemented below. Throughout, we use $\mu > 0$ to denote the multiplier on the Implementability Constraint, which also corresponds to the social value of public funds. Note in addition that this program is convex, meaning that the objective function is strictly concave and the constraint set is convex.

Proposition 1 ***(Optimal capital and labor taxes and automation)*** *The unique solution to the Ramsey problem in* (7) *satisfies*

$$
(8) \qquad \frac{\tau^{k,r}}{1-\tau^{k,r}} = \frac{\mu}{1+\mu}\cdot\frac{1}{\varepsilon^k(k)} \qquad\qquad \frac{\tau^{\ell,r}}{1-\tau^{\ell,r}} = \frac{\mu}{1+\mu}\cdot\frac{1}{\varepsilon^\ell(\ell)} - \frac{\varrho}{1+\mu},
$$

and $\theta^r = \theta^m(k,\ell)$.

The proof of this proposition, like those of all other results in this paper, is provided in the Appendix. The optimal tax formulae in equation (8) follow straightforwardly from working out the solution to the maximization problem in (7). Uniqueness follows from the fact that the objective is strictly quasi-concave and the constraint set is convex.

This proposition provides simple conditions for taxes on capital and labor related to the social value of public funds and the elasticity of supply of these factors. Notably, taxes should be lower for more elastic factors, and in addition, the optimal labor tax is further lowered by the presence of labor market frictions. This latter feature is intuitive: labor market frictions reduce employment beyond the socially optimal level, and the planner corrects for this by reducing labor taxation.

An immediate corollary of this proposition provides one set of sufficient conditions for uniform (symmetric) taxation of capital and labor—$\varepsilon^k(k) \simeq \varepsilon^\ell(\ell)$ and $\varrho \simeq 0$.

Corollary 1 *If* $\varepsilon^k(k) = \varepsilon^\ell(\ell)$ *and* $\varrho = 0$, *uniform taxation of capital and labor is optimal.*

In Section 4 we will see that realistic values of these parameters are not too far from

$\varepsilon^k(k) \simeq \varepsilon^\ell(\ell)$, but labor market imperfections imply $\varrho > 0$, so that our framework yields lower labor taxes than capital taxes in the optimum.[8]

The most important implication of Proposition 1 for our purposes here is that once optimal taxes are imposed on capital and labor, the planner has no reason to deviate from equilibrium automation decisions—$\theta^r = \theta^m(k, \ell)$. This is because any distortions in the labor market are corrected by optimal taxes, and consequently, factor prices accurately reflect the social values of capital and labor, and profit-maximizing automation decisions are optimal as well. We will see that this is no longer true when taxes are not optimal or are subject to additional constraints.

2.4 Excessive Automation with Tax Distortions

Naturally, taxes in practice need not coincide with those characterized in Proposition 1 both because of additional constraints and for political economy reasons (policy-makers have other objectives and face political or other, unmodeled economic constraints). When that is the case, either capital or labor taxes can be (relatively) too low. The interesting case for us, both for conceptual and empirical reasons, is the one where capital taxes are too low and labor taxes are too high, and the necessary and sufficient condition for this follows from equation (8) in Proposition 1 and is presented in the next corollary.

Corollary 2 *If the tax system (τ^k, τ^ℓ) is below the peak of the Laffer curve and satisfies*

$$\frac{\frac{\tau^\ell}{1-\tau^\ell} + \varrho}{\frac{1}{\varepsilon^\ell(\ell)} - \frac{\tau^\ell}{1-\tau^\ell}} > \frac{\frac{\tau^k}{1-\tau^k}}{\frac{1}{\varepsilon^k(k)} - \frac{\tau^k}{1-\tau^k}}, \tag{9}$$

then $\tau^\ell > \tau^{\ell,r}$ and $\tau^{k,r} > \tau^k$—that is, the labor tax is too high and the capital tax too low.

Put differently, inequality (9) is sufficient for the tax system being distorted against labor and in favor of capital.[9] An important implication of such a distorted tax structure

[8] The result that the optimal tax system should not combine significant taxes on labor and zero (or small) taxes on capital extends to a dynamic setting provided that the long-run elasticity of capital supply, ε^k, is not infinite (infinite elasticity is a feature of models with additively separable utility, but not otherwise). Straub & Werning (2020) show that, in a representative household economy where preferences are not time-additive and the tax system is not constrained by other consideration, the optimal taxes on both capital and labor should converge to zero. We prove in the Appendix that this result holds in our setup with automation, and if in addition there are labor market distortions, then optimal taxes should be lower on labor than capital. Hence, even in a dynamic setting, for plausible values of capital supply elasticities, capital and labor should be taxed uniformly, or labor should be favored if there are significant labor market imperfections.

[9] The government budget constraint implies that both taxes cannot be too high or too low at the same time (provided that we are below the peak of the Laffer curve, meaning that tax revenues cannot be increased by lowering both taxes). Thus, inequality (9) is sufficient for $\tau^\ell > \tau^{\ell,r}$ and $\tau^{k,r} > \tau^k$.

(where (9) holds) is that there is too little employment relative to the optimal allocation in Proposition 1, and thus marginal increases in employment will have first-order positive effects on welfare. We exploit this insight in the next proposition, where we take the tax system as given and consider a marginal change in automation. To do this in the simplest possible way, we are relaxing the government budget constraint, (6), and valuing changes in the government budget at the social value of public funds given by the multiplier μ.

PROPOSITION 2 ***(When reducing automation improves welfare)*** *Suppose that the tax system (τ^k, τ^ℓ) satisfies inequality (9) (and is thus biased against labor and in favor of capital). Welfare (inclusive of fiscal costs and benefits) increases following a small reduction in θ below $\theta^m(k,\ell)$. A small reduction in θ also increases output provided that $\varepsilon^\ell(\ell) > \varepsilon^k(k)$ and government revenue provided that $\tau^\ell \cdot (1+\varepsilon^\ell(\ell)) > \tau^k \cdot (1+\varepsilon^k(k))$.*

This is an important result, in part because it qualifies a basic intuition suggested by Proposition 1, which established that with optimal taxes equilibrium automation is optimal. In contrast, when taxes are distorted against labor (in the sense that inequality (9) holds), then it is welfare improving to restrict automation below its equilibrium level. This result is intuitive in light of the observation in Corollary 2 that employment is below the socially optimal level. Specifically, a small reduction in automation will create a first-order welfare gain by shifting demand from capital to labor. Distorting automation is costly, but starting from the equilibrium level of automation, $\theta^m(k,\ell)$, this cost is second-order (since $f_\theta(k,\ell;\theta^m(k,\ell)) = 0$), and hence, a small reduction in automation is welfare improving. This intuition also relates Proposition 2 to the notion of "so-so (automation) technologies" proposed in Acemoglu & Restrepo (2019a,b): automation is not beneficial to labor when it only increases productivity by a small amount, while still creating the usual displacement of workers as tasks are reallocated from them to capital. The equilibrium condition $f_\theta(k,\ell;\theta^m(k,\ell)) = 0$ implies that automation technologies adopted at marginal tasks are, by definition, so-so. The planner is therefore happy to sacrifice some of these so-so technologies in order to help labor.[10]

As we will see in Section 4, the US tax system is comfortably within the range that satisfies inequality (9), so that there are *prima facie* reasons for suspecting that the level of automation may be excessively high in the US economy, as in this proposition.

[10]If automation decisions were constrained by available technology (as in Acemoglu & Restrepo, 2018, 2019a), then we could have $f_\theta(k,\ell;\theta^m(k,\ell)) > 0$ at the equilibrium level of automation $\theta^m(k,\ell)$. In this case, productivity gains from automating marginal tasks could be positive. If they were sufficiently large, then automation would no longer be a so-so-technology and Proposition 2 would not apply. This discussion highlights the role of the task-based modeling of automation in our results.

One common intuition is that when confronted with a tax system with distortions, (τ^k, τ^ℓ), the best policy is to redress these tax distortions directly. We next show that this is not always the case. In particular, if for other reasons taxes on labor cannot be reduced below a certain threshold (which we denote by $\bar{\tau}^\ell$), then the tax system satisfies inequality (9) and is biased against labor, but this does not necessarily imply that capital taxes should be increased. Rather, constrained optimal policy calls for a reduction in the equilibrium level of automation and may even necessitate a *lower* tax on capital. Before presenting this result, let us note that in this case we are imposing $\tau^\ell \geq \bar{\tau}^\ell$, which can be expressed as an additional constraint on the Ramsey problem (7) of the form

$$\nu' \leq (1 - \bar{\tau}^\ell) \cdot (1 - \varrho) \cdot f_\ell. \tag{10}$$

Intuitively, the lower bound on labor taxes translates into an upper bound on the marginal disutility from work. In the next proposition, we denote the multiplier on this constrained by $\gamma^\ell \geq 0$.

Proposition 3 ***(Excessive automation with tax distortions)*** *Consider the constrained Ramsey problem of maximizing (7) subject to the additional constraint $\tau^\ell \geq \bar{\tau}^\ell$, and suppose that in the solution to this problem (10) binds. Then the constrained optimal taxes and allocation are:*

- *a labor tax of $\tau^{\ell,c} = \bar{\tau}^\ell$ and a tax/subsidy on capital that satisfies*

$$\frac{\tau^{k,c}}{1 - \tau^{k,c}} = \frac{\mu}{1 + \mu} \cdot \frac{1}{\varepsilon^k(k)} - \frac{\gamma^\ell}{1 + \mu} \cdot (1 - \bar{\tau}^\ell) \cdot (1 - \varrho) \cdot \frac{f_{\ell k}}{\phi'}, \tag{11}$$

- *a level of automation $\theta^c < \theta^m(k, \ell)$.*

Before discussing the implications of this proposition, we explain the meaning and implications of constraint (10). This constraint being binding implies that, had she been unconstrained, the planner would have chosen a tax rate on labor $\tau^\ell < \bar{\tau}^\ell$. This in turn implies that when the constraint $\tau^\ell \geq \bar{\tau}^\ell$ is binding, it is forcing the tax system to be distorted against labor and in favor of capital (or in other words inequality (9) will hold). This equivalently implies that the level of employment is below what the planner would have chosen in the unconstrained Ramsey problem. All of the results in this proposition are an implication of this distorted tax system.

The first important result following from this proposition is that, given this distorted tax system, the planner wants automation to be less than its equilibrium level. The intuition is identical to that of Proposition 2: the reduction in automation creates a second-order cost but a first-order gain via its impact on increased employment.

The second important result is that the optimal capital tax formula, (11), has an additional negative term on the right-hand side relative to (8). In fact, this negative term can lead not just to lower capital taxes than in the unconstrained Ramsey problem in Proposition 1, but even to capital subsidies.[11] This is because increasing the capital stock used in production, at a given level of automation, is beneficial for labor. In particular, because capital and labor are $q-$complements, greater capital raises the marginal product of labor (and when (9) holds, this is socially beneficial because it raises employment). Hence, all else equal, the planner would like to increase the amount of capital in the economy, even though capital is only used in automated tasks. This is related to the discussion of deepening automation in Acemoglu & Restrepo (2019a): deepening of automation, which means an increase in the productivity of tasks that are already automated (due to technological changes or greater use of capital in these tasks) is always beneficial for labor. What is potentially damaging to labor is an increase in the extent of automation—because this displaces workers from tasks they were previously performing. Proposition 3 builds on this logic: the planner would like to reduce the range of tasks that are automated by reallocating marginal tasks back to labor, and may also want to reduce capital taxes or even subsidize capital.[12]

Proposition 3 focused on the case where there is a lower bound on labor taxation. An equally plausible case is one where because, of political economic influence of capital owners or because of concerns about capital flight, there is an upper bound on capital taxation.[13] Proposition A.3 in the Appendix establishes that in this case too the planner prefers to reduce the equilibrium level of automation. The intuition is similar: the upper bound on capital taxation leads to a tax system biased in favor of capital and against labor, and this makes the displacement of labor by capital in marginal tasks socially costly. Reducing automation then encourages capital to be reallocated to tasks where capital has a comparative advantage, again benefiting labor through $q-$complementarity (as well as by reducing the first-order displacement effects from marginal tasks).

[11]This might at first appear surprising, especially because the program in Proposition 1 is convex, so moving in the direction of the unconstrained optimum should be beneficial. However, convexity is in the space of allocations and does not imply convexity in the space of taxes. Therefore, increasing the tax rate on capital towards $\tau^{k,r}$ is not necessarily welfare-improving.

[12]To put it differently, given k and θ, the employment level can be written as $\ell = \ell^c(k, \theta)$, which is defined implicitly by the solution to equation (10). Then $\ell = \ell^c(k, \theta)$ increases in k, because of the $q-$complementarity between capital and labor, but decreases in θ near $\theta^m(k, \ell)$, because of the first-order displacement effects.

[13]Similar constraints are used in the optimal taxation literature (see, for example, Chamley, 1987; Judd 1999; Straub & Werning, 2020).

2.5 Implementation

To ease exposition, we have so far assumed that the planner can directly control θ. We now discuss how the desired level of θ can be implemented via taxes. Recall that $k(x)$ is the amount of capital of type x, and so far we have assumed that all types of capital are taxed at the same uniform rate, τ^k. In practice, as we discuss in the next section, taxes vary by type of capital (e.g., equipment, software, structures) and industry (because of differential depreciation allowances). In the context of our model, this can be viewed as a task-specific capital tax rate of $\tau^k(x)$. The next proposition shows when such task-specific capital tax rates are useful and in the process further clarifies the nature of (locally) optimal policy interventions.

PROPOSITION 4 ***(Automation tax)*** *Suppose the planner can set task-specific capital taxes and cannot directly control automation decisions. Then:*

1. *Under the conditions of Proposition 1, the planner sets a uniform capital tax rate, i.e.,* $\tau^k(x) = \tau^k$.

2. *Under the conditions of Proposition 3, the planner prefers to depart from uniform capital taxation. In particular, she can implement the level of automation* $\theta^c < \theta^m(k,\ell)$ *with the following tax scheme:*

$$\tau^k(x) = \begin{cases} \tau^k & \text{for } x \le \theta^c \\ \tau^k + \tau^A & \text{for } x > \theta^c \end{cases}$$

where $\tau^A > 0$ *is a task-specific "automation tax".*

The reason (unconstrained) optimal policy has no use for task-specific taxes is intuitive: in the unconstrained Ramsey problem, there is no need to distort equilibrium automation decisions. However, in the presence of additional constraints, the planner would like to reduce automation to $\theta^c < \theta^m(k,\ell)$, and she can achieve this by taxing capital overall, while subsidizing production or capital in tasks below this threshold θ^c. As a result, rather than reducing their use of capital, these tasks use capital more intensively, which then helps labor via the $q-$complementarity.[14] In what follows, we refer to the additional tax on capital τ^A

[14] The fact that the planner would always like to subsidize the use of capital in tasks that are automated follows from the following argument. Using the notation introduced in footnote 12, in addition to its direct effect on output, increasing k raises $\ell = \ell^c(k,\theta)$ (because of $q-$complementarity) and this generates an additional benefit, which calls for further increasing the use of capital in automated tasks. Crucially, this is different from increasing the overall capital stock of the economy, because, all else equal, such an increase would induce further automation in equilibrium. In fact, as already noted, the planner would go in the opposite direction and reduce automation.

as an "automation tax".

3 The US Tax System

In this section, we first introduce the notion of *effective taxes* on capital and labor. Effective taxes summarize the average distortion that the US tax system introduces in the use of capital and labor. We then provide formulas for effective taxes that take into account all of the complex elements of the US tax code and their interaction with the type of financing and ownership structure of the firm making investment decisions.

3.1 Defining Effective Taxes on Capital

In our framework, τ^k is the effective tax on (the use of) capital. It is defined as the wedge that the tax system introduces between the internal rate of return for a firm investing in capital and the after-tax rate of return paid to investors. The US tax system includes several taxes, not just a single effective tax on the use of capital. We have personal income taxes on capital income, corporate income taxes, depreciation allowances and many other instruments that contribute to taxes on different types of capital. Moreover, these taxes vary by form of organization (C-corporation vs. passthrough) and type of financing (equity vs. debt).[15]

We start by providing formulas for effective taxes on the use of capital by type of asset, j, form of organization and type of financing. To simplify the exposition, we assume the economy is in steady state—the capital-labor ratio remains constant, the tax system is not expected to change, the price of capital goods changes at a constant rate $\pi^j = q_t^j / q_{t-1}^j$ and the capital stock of type j depreciates at a constant rate $\delta^j > 0$.

The internal rate of return of investing one dollar in equipment j at time $t-1$ is given by

$$r^{f,j} = \mathrm{mpk}^j - \tilde{\delta}^j$$

where mpk^j is the marginal product of investing one dollar in asset j and $\tilde{\delta}^j = 1 - \pi^j \cdot (1 - \delta)$ denotes the total depreciation of the asset. Let us denote the after-tax steady-state rate of return to investors by r. The effective tax rate on capital of type j, $\tau^{k,j}$, can then be defined as

$$\frac{1}{1 - \tau^{k,j}} = \frac{r^{f,j}}{r} = \frac{\mathrm{mpk}^j - \tilde{\delta}^j}{r}. \tag{12}$$

[15]Passthrough organizations include both S-corporations and other passthroughs, such as sole proprietor businesses and partnerships.

This formula aligns closely with the effective capital taxes in our conceptual framework presented in the previous section. In particular, in equation (4), $\frac{1}{1-\tau^k}$ is equal to the wedge (ratio) between the return to the firm of using capital (given by the marginal product of capital per dollar $f_k/\phi'(k)$) and the return demanded by investors (the marginal utility of consuming that dollar, which is equal to 1). The only difference is that (4) does not contain the term $\tilde{\delta}^j$, because there is no depreciation in our static model. Equation (12) accounts for depreciation by using net (of depreciation) returns in both the numerator and the denominator.[16]

The computation of effective tax rates requires measuring the marginal product of capital. We follow Hall and Jorgenson (1967) and back out the marginal product of capital using a representative firm's first-order condition for investment. Here we need to distinguish between C-corporations and passthrough businesses as well as the source of financing, since each of these combinations implies a different first-order condition for investment as well as a different set of taxes on the income generated from capital.

For C-corporations financing their investment with equity, the first-order condition is

$$\text{mpk}^j = \frac{1-\alpha^j\cdot\tau^c}{1-\tau^c}\cdot\left(r^e+\tilde{\delta}^j\right), \tag{13}$$

where τ^c is the corporate income tax rate and $\alpha^j \in [0,1]$ are discounts from depreciation allowances, which reduce taxable income and are discussed in detail in the next subsection. In the absence of corporate income taxes, this expression is identical to the standard user cost formula. In addition, r^e is the pre-tax return to equity holders. This implies that $r = r^e\cdot(1-\tau^{e,c})$, where $\tau^{e,c}$ is the income tax rate on capital income resulting from ownership of public equity.

Combining the formula for effective taxes in equation (12) with the first-order condition for investment in equation (13), the effective tax rate for an equity financed C-corporation is

$$\frac{1}{1-\tau^{k,j}_{\text{c-corp,equity}}} = \frac{1}{1-\tau^{e,c}}\cdot\left(\frac{r^e+\tilde{\delta}^j}{r^e}\cdot\frac{1-\alpha^j\cdot\tau^c}{1-\tau^c}-\frac{\tilde{\delta}^j}{r^e}\right). \tag{14}$$

The formula shows that the effective tax on capital depends on the taxation of capital income of equity owners, corporate income tax rates and depreciation allowances. It reiterates that

[16] An alternative is to use a formula for effective taxes based on gross returns: $\frac{1}{1-\tau^{k,j}_{\text{gross}}} = \frac{\text{mpk}^j}{r+\tilde{\delta}^j}$. All of our results can be expressed in terms of gross returns, but this would require adjusting the empirical estimates of capital supply elasticities, which are in terms of net returns (because the relevant empirical studies use the net rate of return received by households).

depreciation allowances can significantly offset corporate taxes. For example, with immediate (full) expensing (which corresponds to $\alpha^j = 1$), we would have $\tau^{k,j}_{\text{c-corp,equity}} = \tau^{e,c}$.

The main difference for passthrough businesses is that these organizations do not pay the corporate income tax and are only subject to personal income taxation. Depreciation allowances in this case lower personal income tax obligations for the owners of these businesses. The formula for the effective tax on the use of capital for a passthrough business that is financing its investment with (private) equity is

$$\frac{1}{1-\tau^{k,j}_{\text{passthrough,equity}}} = \left(\frac{r^e + \tilde{\delta}^j}{r^e} \cdot \frac{1-\alpha^j \cdot \tau^{o,p}}{1-\tau^{o,p}} - \frac{\tilde{\delta}^j}{r^e} \right), \tag{15}$$

where $\tau^{o,p}$ denotes the individual tax rate on the income of owners of passthrough businesses. Note again that with immediate expensing ($\alpha^j = 1$), we have $\tau^{k,j}_{\text{passthrough,equity}} = 0$.

We next turn to debt-financed investments, which allow a further tax discount by subtracting interest payments from taxable income. The presence of these additional tax discounts modifies the first-order condition for investment to

$$\text{mpk}^j = \frac{1-\alpha^j \cdot \tau^c}{1-\tau^c} \cdot \left(r^b \cdot (1-\tau^c) + \tilde{\delta}^j \right), \tag{16}$$

where r^b is the return offered to bond-holders and $r^b \cdot (1-\tau^c)$ incorporates the lower tax liabilities (which is multiplied by the corporate income tax rate τ^c faced by C-corporations). Note that the after-tax return to households that own bonds is given by $r = r^b \cdot (1-\tau^{b,c})$, where $\tau^{b,c}$ is the personal income tax rate for capital income from C-corporation bonds.

Combining the formula for effective taxes in equation (12) with the first-order condition for investment in equation (16), the effective tax rate for a debt-financed C-corporation is

$$\frac{1}{1-\tau^{k,j}_{\text{c-corp,debt}}} = \frac{1}{1-\tau^{b,c}} \cdot \left(\frac{r^b \cdot (1-\tau^c) + \tilde{\delta}^j}{r^b} \cdot \frac{1-\alpha^j \cdot \tau^c}{1-\tau^c} - \frac{\tilde{\delta}^j}{r^b} \right). \tag{17}$$

The effective tax on capital again depends on the personal income tax rate of bond-holders, corporate income tax rates, interest rate reductions and depreciation allowances. The additional tax discounts can easily lead to a net subsidy to the use of capital. In particular, with immediate expensing ($\alpha^j = 1$), we have $\tau^{k,j}_{\text{c-corp,debt}} \approx \tau^{b,c} - \tau^c$, which is negative if bond-holders face lower individual tax rates than corporations.

Owners of passthrough businesses can also subtract their interest payments on debt from their taxable income. However, if they issue bonds, payments to bond-holders are subject to personal income taxation. The formula for the effective tax on the use of capital for a passthrough business that is financing its investment with debt is thus similar to that of a C-corporation and given by

$$\frac{1}{1-\tau^{k,j}_{\text{passthrough,debt}}} = \frac{1}{1-\tau^{b,p}} \cdot \left(\frac{r^b \cdot (1-\tau^{o,p}) + \tilde{\delta}^j}{r^b} \cdot \frac{1-\alpha^j \cdot \tau^{o,p}}{1-\tau^{o,p}} - \frac{\tilde{\delta}^j}{r^b} \right), \tag{18}$$

where $\tau^{b,p}$ denotes the individual income tax rate applying to holders of passthroughs' bonds. As before, with immediate expensing ($\alpha^j = 1$), we would have $\tau^{k,j}_{\text{passthrough,debt}} \approx \tau^{b,p} - \tau^{o,p}$, which is negative if bond holders face lower income taxes than the owners of passthrough businesses.

3.2 Computing Effective Taxes on Capital

We compute effective taxes for equipment, software and structures separately. For each type of capital good, we compute effective taxes by form of organization and type of financing, and then aggregate these taxes into a single effective tax rate for the relevant type of capital using investment shares as weights. The Appendix provides a detailed list of the sources and numbers used in our calculation. Here we outline the computation of the main ingredients that determine effective taxes on capital: depreciation allowances, α^j; corporate income taxes and taxes on owners of equity and passthroughs; and interest rates, economic depreciation and investment prices.

Depreciation allowances: The tax discount term, α^j, is equal to the present discounted value of depreciation allowances associated with one unit of capital purchased at time t, which can be computed as

$$\alpha^j = d^j_0 + \sum_{s=0}^{\infty} d^j_{s+1} \cdot \prod_{\tau=0}^{s} \frac{1-d^j_\tau}{1+r}, \tag{19}$$

where d^j_s denotes the fraction of the investment that a firm gets to subtract from its tax liabilities s years after the purchase.

One useful benchmark is given by the case where firms can subtract the economic depreciation of their capital goods each period. In the above formula, this means $d^j_0 = 0$ and a constant depreciation rate of δ^j from there on, which adds up to a present discounted value of $\tilde{\alpha}^j = \delta^j/(\delta^j + r) < 1$.

In practice, the IRS and the US tax code handle depreciation allowances quite differently from this benchmark. The way in which depreciation allowances are determined is specified in IRS Publication 946. The current system places each type of capital under a specific *class life*—the number of years that a new unit of capital lasts for tax purposesbased on its characteristics and sector. The first reason why tax discounts α^j differ from the one given by constant economic depreciation, $\tilde{\alpha}^j$, is that the depreciation rate implied by a class life is different from the economic depreciation rate.

A second reason generating an additional tax discount is that the tax code requires taxpayers to follow specific depreciation schedules and enables front-loading of allowances. When computing their tax discount, firms may use a combination of *straight-line* and *declining-balance* methods that yields the highest possible discount. The straight-line method allows firms to expense a constant fraction of their *initial* investment (or undepreciated investment in the *initial* year in which the method is applied) for each year of remaining tax life. The declining-balance method can be used for assets with a class life below 20 years, and allows firms to front-load their depreciation allowances by expensing a decreasing fraction of their initial investment each year. Assets in a class life of 10 years or less can be depreciated using a 200% declining-balance rule, which allows firms to expense their undepreciated investment at two times the rate prescribed by the straight-line method (2×10% for an asset in a class life of 10 years). Firms can then switch to the straight-line method near the end of the asset life to maximize their allowances.[17] Assets with a class life between 10 and 20 years, on the other hand, can be depreciated using a 150% declining-balance rule, while assets with a class life of more than 20 years adhere to the straigh-line method.

The third and final reason generating large discounts from depreciation allowances are recent changes in legislation, passed as part of economic stimulus plans, which introduced *bonus depreciation*.[18] Under current bonus depreciation provisions, most capital with a class life below 20 years enjoys a 100% bonus depreciation, meaning that investors can immediately expense their capital purchases as current costs. This immediate expensing

[17] As an example, consider the allowances generated by the purchase of a machine with a class life of 10 years. Suppose the purchase takes place in the middle of the year. The straight-line method allows a deduction of 5% of the cost in the first year, 10% for the following nine years, and 5% on the eleventh year. The 200% declining balance method gives an allowance of 10% in the first year (two times the straight-line rate of 5%), 18% in the second year (two times the straight-line rate of 10% times the undepreciated stock, 90%), 14.4% in the third year (two times the straight-line rate of 10% times the undepreciated stock, 72%). This continues up to year 7, where the method prescribes an allowance of 5.89%, which is below the straight-line method allowance of 6.55% computed on the undepreciated stock of capital and 4.5 years of useful life left. Therefore, the schedule for 10-year property follows the 200% declining-balance method until year 7 and switches to a constant allowance of 6.55% of the undepreciated cost for the remaining 4.5 years. For further discussion and examples on the declining-balance method, see the Appendix in House and Shapiro (2008).

[18] In particular, the "Job Creation and Worker Assistance Act of 2002" (JCWAA) introduced a 30% bonus depreciation for 2002-2003; the "Jobs and Growth Tax Relief Reconciliation Act of 2003" (JGTRRA) raised the bonus to 50% for 2004; the "Economic Stimulus Act of 2008" introduced a 50% bonus, which was extended until 2017 by successive bills; the "Tax Relief, Unemployment Insurance Reauthorization, and Job Creation Act of 2010" temporarily raised the bonus to 100% (full expensing) between September 2010 and the end of 2011. Finally, the "Tax Cuts and Jobs Act of 2017" raised the bonus depreciation to 100% for 2018-2022.

yields a maximum discount of $\alpha^j = 1$.[19]

We compute α_t^j for 1980–2018 for each type of capital taking into account changes in the treatment of depreciation allowances and bonus depreciation programs (excluding the further reductions in effective capital taxes generated by the 2017 tax reforms, since these did not affect the automation decisions throughout the 2010s). When computing α_t^j, we assume that firms expect no future changes to their tax code, so that they expect future discounts to apply to their current rate.[20]

Figure A.1 in the Appendix plots $\tilde{\alpha}^j$ and α^j for software, equipment, and non-residential structures. The figure show that α^j typically exceeds $\tilde{\alpha}^j$ for software and equipment, and that recent bonus depreciation provisions generated an increase in allowances bringing α^j close to 1 for software and equipment in the 2010s.

Tax rates on corporations and capital owners: Effective taxes on capital also depend on taxes on corporations and the households who own capital. We approximate the average marginal corporate income tax rate τ_t^c for each year as the average tax paid by C-corporations:

$$\tau_t^c = \frac{\text{corporate tax revenue}}{\text{net operating surplus of C-corporations}}.$$

The corporate tax revenue are obtained from NIPA Tables. The computation of the tax base is presented in the Appendix. We start with operating surplus from corporations and subtract depreciation allowances. We then allocate a fraction of these profits to C-corporations using data from the IRS on profits by type of corporation. The remaining share is accounted for by S-corporations which do not pay corporate income taxes and is not included as part of the tax base in the above calculation. The share of corporate profits generated by C-corporations has fallen over time from 93% in 1980 to 61% in 2018, in line with the findings Smith et al. (2019). Our computations show that once we account for this changing share, the average tax rate on C-corporations increased from 25% in 1981 to 35% in 2000, and then declined to 17.5% in 2018.

Note that we are computing corporate income taxes as an average of the taxes paid, and not by using the statutory rate (46% in 1981, 35% in the intervening years, and 21% in

[19] A 100% bonus depreciation corresponds to $d_0 = 1$ and $d_s = 0$ for all $s > 0$ in equation (19). As stated above, capital allowances are generally set by the schedules in Publication 946, which give a specific d_s^j for all s, j, such that $\sum_{s=0}^{T_j} d_s^j = 1$, for each investment type j, and where T_j is the class life for the capital type j. When bonus depreciation is $\gamma < 1$, the taxpayer obtains a first-year bonus allowance equal to γ and then follows the schedules for depreciation allowances for the undepreciated capital stock. Therefore, the bonus allowance series, $\tilde{d}_s^j$, has $\tilde{d}_s^j = (1-\gamma)d_s^j$, for all $s \geq 1$, and $\tilde{d}_s^j = \gamma + (1-\gamma)d_0^j$ in the initial period.

[20] In particular, if future tax reforms are anticipated, this creates a "reevaluation" effect for capital that is already installed.

2018). This is because many corporations pay less corporate income tax than implied by the statutory rate. Throughout, we interpret average taxes as averages of marginal tax rates faced by different types of firms.

Besides taxes paid by corporations, taxes paid by households on their capital income from equity and lending also contribute to the effective tax on the use of capital (the terms $\tau^{e,c}$, $\tau^{b,c}$ and $\tau^{b,p}$ in equations (14), (17) and (18)). We compute $\tau^{e,c}$ as the average tax rate paid by owners of equity on their dividends and capital gains. We start by computing the share of corporate equity that is directly held by US households and is thus subject to taxation. Using data from the Board of Governors of the Federal Reserve System, we compute this as the share of corporate equity owned by US households and nonprofit organizations serving these households, which has fallen from 58% in 1981 to 37% in 2018. We follow CBO (2014) and assume that the remaining share is owned by funds or kept in accounts that are not subject to additional taxation.

Taxes paid by households depend on how corporate profits are realized. Qualified dividends or capital gains are taxed at a *maximum capital gain tax rate* specified by the IRS.[21] These include dividends on stocks held by more than 61 days, or capital gains on stocks owned for over a year. Ordinary (non-qualified) dividends or capital gains apply to stock owned over shorter periods and are taxed at the same rate as individual income. The remaining profits represent stock held until death, whose capital gains are never realized and thus face of taxation. We compute the share of profits realized through ordinary dividends and short-term capital gains by using data from the IRS Individual Complete Report (Publication 1304, Table A) for the period 1990-2017 and the IRS SOI Tax Stats (Sales of Capital Assets Reported on Individual Tax Returns) for the period 1990-2012. Publication 1304 reports households' ordinary dividend income from corporate stocks, while the SOI Tax Stats reports the short-term capital gains on corporate stocks. Short-term dividends and ordinary capital gains account for the bulk of realized profits from ownership of C-corporations (about 60% in recent years). The remaining share of profits correspond to long-term qualified gains and dividends, or to stocks held until death whose capital gains are never realized. We assume that each of these two forms accounts for an equal share of profits, which aligns with what the CBO reports for 2011.

The average tax rate on profits derived from C-corporation profits (after paying corporate

[21] The maximum capital gain tax rate is presented in IRS publication 550, and represents a sizable discount on the regular tax rate. In 2018, taxpayers facing a marginal tax rate below 15% had a maximum capital gain rate of 0%. Taxpayers facing a marginal tax rate between 22% and 35% had a maximum capital gain tax rate of 15%. Finally, taxpayers facing a marginal tax rate of 35% faced a maximum capital gain tax rate of 20%.

taxes) is thus given by

$$\tau_t^{e,c} = \begin{matrix}\text{share directly}\\ \text{owned}_t\end{matrix} \cdot \left(\begin{matrix}\text{share short-}\\ \text{term ordinary}_t\end{matrix} \cdot \tau_t^o + \begin{matrix}\text{share long-}\\ \text{term qualified}_t\end{matrix} \cdot \tau_t^q + \begin{matrix}\text{share held}\\ \text{until death}_t\end{matrix} \cdot 0\% \right)$$

Here, τ_t^o is the average tax rate on short-term ordinary capital gains and dividends, and τ_t^q is the average tax rate on long-term qualified capital gains and dividends. Both average taxes are computed using data from the Office for Tax Analysis for 1980–2014. In recent years, the average tax rate on ordinary short-term gains and dividends was $\tau_t^o = 24\%$ and the average tax rate on long-term qualified capital gains and dividends was $\tau_t^q = 18\%$. Our estimates show that $\tau_t^{e,c}$ has hovered around a historical average of 15% and experienced a temporary reduction to 12.5% during the 2000s.

Turning to taxation of rental income for bond-holders, the CBO estimates that a fraction 52.3% of C-corporation bonds are held directly by households, a share 14.9% is temporarily deferred for tax purposes, and the rest is held by funds or kept in accounts that are not subject to additional taxation. For passthrough entities, the share owned by households is larger and equal to 76.3%, and the share deferred is 10.1%. Moreover, the CBO reports that the rental income owned by households is subject to personal income taxes, which applied at a rate 27.4% in 2014. Assuming that temporarily deferred income is subsequently taxed at the same rate as the rest of rental income, we estimate the average tax paid by bond-holders on their rental income as $\tau^{b,c} = 16.84\%$ and $\tau^{b,p} = 23.25\%$, and assume that this has remained constant over time.

The final item required for our calculations is the tax rate paid by owners of passthroughs, which we separate into S-corporations and other passthroughs (sole proprietor businesses and partnerships). Profits from S-corporations are taxed at the individual income rate of the owners. We assume that the average tax rate paid by owners of S-corporations is the same as the average tax paid by individuals earning ordinary short-term dividends and capital gains, τ_t^o.[22] In economic terms, this requires owners of S-corporations to have a similar income profile as investors in public equity. In addition, part of the profits generated by S-corporations accrue only when the company is sold, and these profits are taxed at the maximum qualified rate, τ_t^q. Thus, we measure the average tax paid by owners of S-

[22]The profits from S-corporations is also taxed as corporate income by some states. To account for this, we add the average state and local tax rate on businesses, which we compute by dividing the net operating surplus of corporations by state and local revenue from business taxes. State and local taxes on businesses are small in practice, with an average value near 3% in recent years.

corporations on their profits as

$$\tau^{o,s} = \tau_t^o - \text{share capital gains} \cdot (\tau_t^o - \tau_t^q).$$

Using data on sales of passthrough businesses reported by the IRS for 1990–2000, we estimate the average share of capital gains in S-corporation profits as 25%, and assume it has remained at this level over time. Our estimates imply that $\tau_t^{o,s}$ has been roughly constant over time at a level of 27% and reaching 28% in 2018. Since self-proprietors' and partnerships income is reported as personal income, we have no data on the tax rate faced by owners on their profits and so we assume that they face the average tax rate on income (obtained from the IRS, SOI Tax Stats), which has been approximately 14.6% in recent years.

Overall, our estimates imply that in 2011 the average corporate income tax was 26.4% (with equity holders paying an additional 11.8% on top of this), the average tax rate paid by S-corporation owners was 23%, and the average tax rate paid by owners of other passthroughs was 14.6%. These numbers align closely with those by the CBO and Cooper et al. (2016).[23]

Interest rates, depreciation and investment prices: We assume a constant interest rate, a constant growth rate for investment prices and a constant rate of economic depreciation for each asset that match historical averages from 1981 to 2017. We use a constant value of $r^b = 4.21\%$ per annum for bond-holders, given by the average of the Moody's Seasoned AAA Corporate Bond Yield minus realized inflation between 1981 and 2017. Likewise, we use a constant value of $r^e = 4.36\%$ per annum for equity-holders, which is the historical average of the real rate of return on the S&P 500 over 1957–2018. The constant growth rate for investment prices is estimated from the average change of investment price indices by type of capital from the BEA Fixed Asset Tables (FAT) between 1981 and 2017. These imply an annual average growth rate of prices equal to -1.6% for software, -1% for equipment, and 2% for non-residential structures. The economic depreciation rates, the δ_t^j's, are taken directly from the BEA FAT as the averages for 1981-2017 (the average depreciation rate per annum is 23.4% for software, 13.9% for equipment, and 2.6% for non-residential structures).

3.3 Effective Taxes on Labor

In our model, τ^ℓ is the effective tax on (the use of) labor. However, as with capital, there is no single tax on labor in the US tax code. Instead, labor income is subject to a number of

[23] Using IRS data, Cooper et al. estimate that in 2016 C-corporations paid an average tax rate 23% (plus 8.25% on the household side), S-corporations paid an average tax rate of 25% and other passthroughs paid an average tax rate of about 14.7%.

different taxes both at the federal and local level, and means-tested public programs may also generate additional implicit taxes on labor. The effective tax on labor is given by the wedge that the tax system introduces between the marginal product of labor and the before-tax wage, mpl^f. The representative firm will demand labor until the marginal product of labor, mpl^f, equals the cost of one unit of labor given by total compensation. That is,

$$\mathrm{mpl}^f = \text{compensation} = \text{salary} + \text{benefits}.$$

Wage income is subject to personal income tax at a rate τ^h, and payroll taxes at a rate τ^p. Benefits are not taxed, but might be imperfectly valued by workers, which we capture by converting them to an income-equivalent amount by multiplying it with $\varphi \in [0,1]$. Consequently, the after-tax return to work for the household is given by

$$w = \text{salary} \cdot (1 - \tau^h - \tau^p) + \text{benefits} \cdot \varphi.$$

The effective tax rate on labor is defined analogously to the effective tax on capital as

$$\frac{1}{1-\tau^\ell} = \frac{\mathrm{mpl}^f}{w} \Rightarrow \tau^\ell = \frac{\text{salary} \cdot (\tau^h + \tau^p) + \text{benefits} \cdot (1-\varphi)}{\text{compensation}}.$$

We measure the quantities in this expression as follows. From national accounts we obtain data on salaries and total compensation for the corporate sector. We treat employers' contributions to pensions and health insurance as part of the benefits since these are not taxed. We assume that workers outside the corporate sector receive a similar split between benefits and salaries and are therefore subject to the same effective taxes. We use a payroll tax rate of 15.3%, which is the statutory rate that automatically applies to all earners with an income below $132,900 dollars in 2018 (a level that roughly matches the 95th percentile of income). Since the vast majority of jobs at-risk of automation are performed by workers in the middle of the income distribution, the payroll tax of 15.3% is relevant for automation decisions and is incorporated in our effective tax rate on labor. We measure the personal income tax rate τ^h, consistently with our treatment of payroll taxes, as the average income tax paid by earners below the 95th percentile. This is computed from publicly available data from the IRS for 1986–2017. The estimate for τ^h has been stable in recent years at a level close to 10%.[24]

Finally, we use a value of $\varphi = 0.65$ building on estimates from Gruber and Krueger

[24] If we were to use the average payroll tax (about 10% in recent years) and the average income tax (about 14.6% in recent years), we would end up with a very similar effective tax rate on labor.

(1991), Goldman et al. (2005) and Lennon (2019), which suggest that one dollar of spending on benefits is valued on average at 65 cents by households. This increases our estimates for τ^ℓ by 3%.

Besides our baseline estimate for τ^ℓ described above, we present another estimate for the effective tax on labor which incorporates the implications of means-tested welfare programs. In particular, there is a wide range of programs, including cash transfers and tax credits, that are faced out as individual income increases, and various programs (such as disability insurance and unemployment insurance) in which individuals participate less when labor demand is high (see for instance the evidence in Autor & Duggan, 2003; Autor, Dorn & Hanson, 2013; and Acemoglu & Restrepo, 2020a). As a consequence, transfers decline as labor demand rises, which acts as an additional implicit tax on labor, τ^d. Austin, Glaeser and Summers (2018) estimate that the extra public expenditures resulting from a person going into non-employment was of \$4,900 per year between 2010–2016 (\$6,300 for those in long-term non-employment and \$2,300 for the short-term unemployed). This is roughly 8% of the average yearly worker compensation during this period, suggesting that social expenditure and disability insurance add a 8% tax to labor. We incorporate this additional source of implicit labor income taxation in our robustness analysis in the Appendix.

3.4 Effective Tax Rates in the US

Figure 1 depicts the evolution of the average personal income tax and average capital tax rates for C-corporations (including both corporate income taxes and personal income taxation) and for S-corporations (whose owners only pay personal income taxes and some state-level taxes). Taxes on C-corporations' profits decline significantly from 2000 onwards, reflecting declines in the statutory corporate income tax rate over time. Taxes on passthrough profits have remained stable around 25% and the average individual income tax has remained close to 15%.

Figure 2 presents our estimates for the effective tax rates on labor and different types of capital (in turn computed from effective tax rates on capital and depreciation allowances for C-corporations, S-corporations and other passthrough businesses, and the differential taxation of capital financed with debt and equity). The solid lines show the effective taxes on software, equipment, non-residential structures and labor.

Several points about these effective tax rates are worth noting. First, effective taxes on equipment and software are low compared to the effective taxes on labor. Our benchmark effective tax on labor (which does not include the implicit taxes implied by means-tested

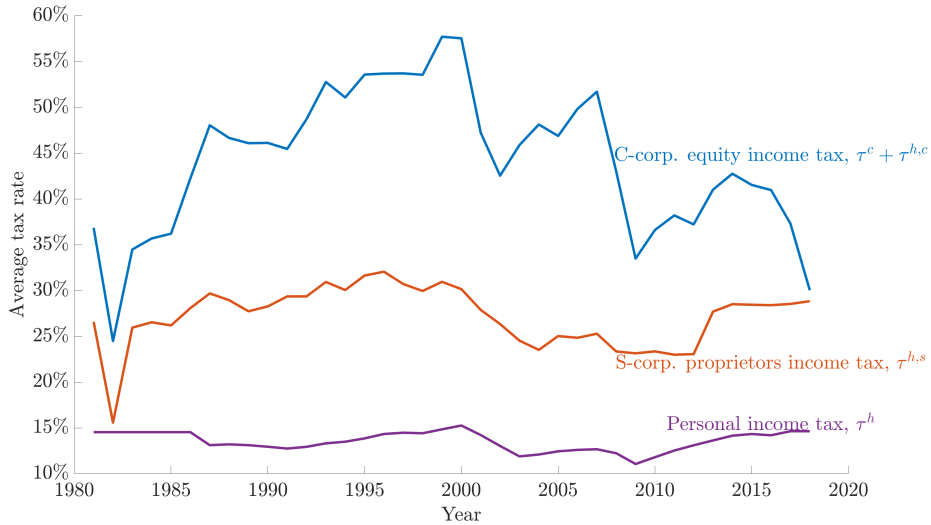


Figure 1: Average tax rates on capital income, corporate income and personal income, 1981-2018.

Notes: See the text for the definitions and sources.

programs) hovers around 25.5%.[25] In contrast, effective taxes on both equipment capital and software in the 2010s (and before the tax reform of 2017) are around 10%.[26] Second, effective taxes on equipment and software were higher in the 1990s and early 2000s, and declined significantly thereafter. This decline is mostly because of the reforms summarized in footnote 18, which have increased depreciation allowances. The dashed lines illustrate the contribution of these reforms by plotting the (counterfactual) effective taxes on different types of capital that would have applied had the treatment of depreciation allowances remained as it was in 2000. Third, effective taxes on equipment and software decreased further, to about 5%, following the 2017 tax reform, which introduced immediate expensing of these capital expenditures. Finally, because depreciation allowances for structures are lower, the effective tax on non-residential structures is higher today than tax rates on equipment and software, but in the past the ordering was reversed (in particular, effective tax rates for non-residential structures were lower in the 1990s).

For our purposes, effective tax rates on equipment and software are more relevant, since

[25] Our estimates imply that the net tax revenue collected by the government with these instruments is roughly 18.6% of GDP (25.5% × labor income in GDP +10% × net capital income in GDP). This figure matches closely the sum of the average share of personal income taxes, corporate taxes and social security contribution in GDP for the period considered in our study (18.7% for 1981–2018 in NIPA Table 3.1).

[26] These effective tax rates are lower than those reported in CBO (2014). Two factors explain the differences. First, and most importantly, the CBO does not incorporate bonus depreciation allowances (based on the argument that these may not be extended in the future). Second, the CBO uses the statutory rate of corporate income tax. As noted above, we do not believe this gives an accurate estimate of the effective tax on capital, since most corporations pay less than the statutory rate.

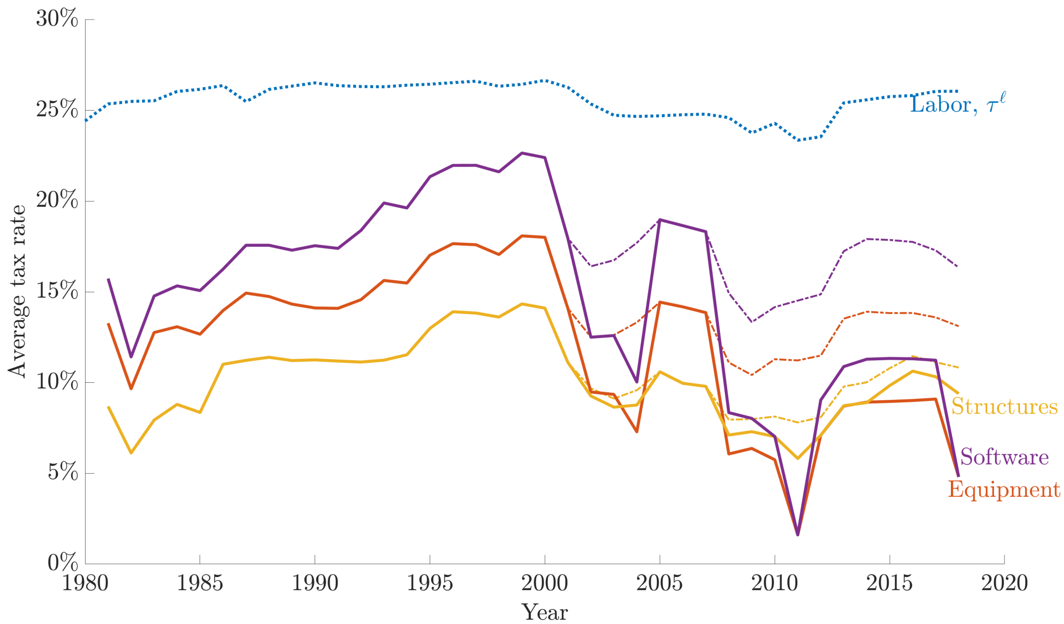


Figure 2: Effective tax rates on labor, software capital, equipment, and non-residential structures.

Notes: The solid lines depict the observed effective taxes. The dashed lines present the effective taxes that would result if the treatment of allowances had remained as in the year 2000. See the text for definitions and sources.

these are the types of capital that are involved in automation. In what follows, we will summarize the US tax system as setting an effective tax on labor of $\tau^\ell = 25.5\%$ and an effective tax on capital of $\tau^k = 10\%$ (the level before the 2017 tax reforms). We will also discuss the implications of the reforms in the 2000s and the 2017 tax reform.

4 Does the US Tax Code Favor Automation?

In this section, we investigate whether the current US tax system excessively favors automation and derive the implications of a tax system that is less biased against labor for employment and welfare. We start by deriving the empirical counterparts of the optimal tax rates in Proposition 1 using a range of micro elasticities.

4.1 Parameter Choices

We first review the empirical literature relevant for the elasticities necessary for computing optimal taxes on capital and labor in our model.

One of our key parameters is λ, which corresponds to the *short-run* elasticity of substitution between capital and labor. Specifically, this is the elasticity of substitution between capital and labor holding the amount of automation (and more generally the state of technology) constant, and without any compositional changes (for example, between firms with different technologies or between industries). Under the assumption that, in the short run, the allocation of tasks to factors is fixed in an establishment, this elasticity can be approximated by the short-run elasticity of substitution within establishments, which is estimated to be $\lambda = 0.5$ in Oberfield and Raval (2014). We use this as our benchmark parameter value.

The other important building block of the production side of our economy is given by the comparative advantage schedules for labor and capital, $\psi^{\ell}(x)$ and $\psi^{k}(x)$. We reduce the dimensions of these functions by assuming that they take iso-elastic forms:

$$\frac{\psi^{\ell}(x)}{\psi^{k}(x)} = A \cdot x^{\zeta} \qquad\qquad \psi^{\ell}(x) = A \cdot x^{\zeta \upsilon},$$

where $\zeta \geq 0$ controls how the comparative advantage of labor changes across tasks, and υ controls the relationship between the comparative and absolute advantage of labor. We take $\upsilon = 1$ as our baseline, which implies that labor is absolutely more productive at higher-index tasks (where it also has a comparative advantage), while capital has a constant productivity across tasks (as in Acemoglu & Restrepo, 2018). We explored the implications of the opposite case in which $\upsilon = 0$ and labor has an absolute disadvantage in tasks where it has a comparative advantage. The results are reported in the Appendix and are similar (and if anything more pronounced) across these configurations, and thus we focus on $\upsilon = 1$ here.

The parameter of comparative advantage ζ (together with λ) shapes the long-run substitution possibilities between capital and labor. In the medium/long run changes in factor prices will lead to endogenous development and adoption of automation technologies, and as the allocation of tasks to factors changes, there will be greater substitution between capital and labor than implied by λ. The extent of this greater substitution is shaped by the comparative advantage of labor across tasks. In particular, since $\lambda = 0.5$, a lower user cost of capital will increase the labor share of national income in the short run (because capital and labor are gross complements given θ), but as automation (θ) adjusts, the labor share could end up lower than it was before the change. Karabarbounis and Neiman (2014) estimate that a 10% reduction in the user cost of capital lowers the labor share by 0.83-1.67 percentage points in the long run. This relationship is consistent with our model when $\zeta = 2.33$.[27] Finally, we set the constant A to match the average labor share (around 60%).

Turning to labor market imperfections, recall that the wedge ϱ captures the difference

[27] More specifically, these authors use a constant elasticity of substitution aggregate production function without automation or reallocation of tasks, and show that their estimates correspond to a long-run elasticity of substitution in the $1.2 - 1.5$ range. In our model, their lower-end estimate implies $\zeta = 2.33$.

between the wage earned by workers and their opportunity cost. This motivates measuring ϱ as the (average) permanent earning loss from job separation. The majority of the estimates of these earning losses in the labor literature are within the range 5%-25% with a midpoint of 15%.[28] Motivated by this evidence, we choose a baseline value of $\varrho = 0.15$.[29]

The remaining parameters of our framework are the elasticities of labor supply and capital. We choose iso-elastic forms for the disutility from work and for the cost of supplying capital:

$$\nu(\ell) = \frac{\varepsilon^{\ell}}{1+\varepsilon^{\ell}} \cdot \ell^{1+1/\varepsilon^{\ell}} \qquad\qquad \phi(k) = \frac{\varepsilon^{k}}{1+\varepsilon^{k}} \cdot k^{1+1/\varepsilon^{k}}.$$

This formulation implies that the elasticity of the capital supply is $\varepsilon^k \geq 0$ and the (Hicksian) elasticity of the labor supply is $\varepsilon^{\ell} \geq 0$. This Hicksian elasticity is the relevant one in our context because we are focusing on permanent tax reforms.[30] Furthermore, because our model does not distinguish between the intensive (hours conditional on employment) and extensive margin (employment), we use the combined elasticity for total hours of work. Chetty et al. (2013) report *micro elasticity* estimates, obtained from differences in tax rates and wages across regions and demographic groups within a country, in the range 0.46-0.76 (of which 0.33 comes from the intensive margin and 0.13–0.45 comes from the extensive margin). These numbers are close to *macro elasticity* estimates obtained from tax differences across countries, which are also around 0.7.[31]

The parameter ε^k corresponds to the long-run elasticity with which the supply of capital

[28] Couch and Placzek (2010) survey this literature and also present their own estimate, suggesting a long-run earning declines from separations of 5%. Jacobson, Lalonde, and Sullivan (1993) find long-run earning declines of about 25%. Davis and von Wachter (2011) report a long-run earning loss of 10% in normal times and 20% in recessions.

[29] Some of the earning losses may be due to loss of firm-specific human capital. If productivity gains from firm-specific human capital are shared equally between firms and workers, these would also create a wedge identical in reduced form to our ϱ.

We also note that there are other factors that would act like a wedge, generating additional incentives to raise employment. These include negative spillovers from non-employment on family, friends and communities and on political behavior (see Austin, Glaeser and Summers, 2019). Because quantifying these effects is more difficult, we are ignoring them in the current paper.

[30] Recall that the Hicksian elasticity measures the response of labor supply to permanent changes in wages and thus includes income effects. This is different from the intertemporal elasticity of labor supply — the Frisch elasticity — which focuses on short-run variations in wages at business cycle frequencies (and thus abstracts from income effects). Because income effects appear to be small (see Imbens et al., 2001), both elasticities are of similar magnitude (Chetty, 2012).

[31] In practice, there could be non-linearities in supply elasticities (see, for example, Mui and Schoefer, 2019), and there is of course uncertainty about the exact supply elasticities. We therefore explore the implications of labor supply elasticities between 0.46 and 1 in our robustness checks.

We should further note that, in the presence of some types of labor market frictions, the extensive margin changes in employment may take place off the labor supply curve, while intensive margin changes are on the labor supply curve. In the Appendix we verify the robustness of our results to incorporating this possibility.

responds to changes in in net returns $d\ln k/d\ln r$ (and is thus different from the "demand-side" elasticities that are informative about how much investment or capital at the firm level will respond to the user cost of capital). A number of recent papers estimate the medium-run (supply-side) elasticity of capital by exploiting reforms that change taxes on wealth for different groups of households. These studies report medium-run elasticities that range from 0.2 to 0.65 over 4–8 year periods (see Zoutman; 2018, Duran-Cabré et al., 2019; Jakobsen et al., 2020).[32] Using a calibrated life-cycle model and assuming a net after-tax return of $r = 5\%$, Jakobsen et al. show that their medium-run estimates are consistent with long-run elasticities ranging from 0.58 for the wealthy and 1.15 for the very wealthy. With a lower-tax net return of 4% (in line with the numbers used in our computation of net effective taxes), long-run capital supply elasticities would be even lower, and conversely, with an after-tax rate of return of 7%, these elasticities would range between 1, for moderately rich households, and 1.9, for very wealthy households (see Table III in Jakobsen et al., 2020). We set our baseline capital supply elasticity to 0.65, which is the average elasticity for the wealthy in Jakobsen et al.'s preferred scenario with $r = 5\%$ and lies at the upper end of the medium-run elasticities reported above.[33] We explore the robustness of our results to using a higher elasticity of capital supply in the Appendix.

4.2 Is the US Tax System Biased against Labor?

We first confirm that the US tax system (with effective taxes $\tau^\ell = 25.5\%$ and $\tau^k = 10\%$) is biased against labor—and has in fact become more biased over time. In particular, using the elasticity estimates presented in the previous subsection, $\varepsilon^\ell = 0.7$ and $\varepsilon^k = 0.65$, inequality (9) is comfortably satisfied. As our theoretical discussion in Section 2 highlighted, this will have important consequences for the level of automation and for whether reducing automation is welfare-improving.

We next illustrate that for a series of plausible variations on our key parameters, inequal-

[32] These estimates are from small and fairly open economies, such as Denmark, the Netherlands and Catalunya, and thus presumably include the response due to the international mobility of capital.

[33] We view our baseline choice as conservative given other estimates in the literature. Brülhart et al. (2019) estimate the elasticity of capital to after-tax returns using variation across Swiss Cantons and municipalities. They estimate an elasticity of 1.05 but also show that about a quarter of the effects are driven by migration across cantons and do not involve a change in overall capital accumulation—which is arguably the relevant margin for optimal taxation in a large economy. In their concluding remarks, they argue that once this response is accounted for, their estimates are comparable to the medium-run estimates of Jakobsen et al., (2020). Kleven and Schultz (2014) estimate an elasticity of capital supply with respect to one minus the tax rate on capital income of 0.3, which would imply an even more inelastic response of capital, reinforcing our results. Finally, a related literature finds small elasticities of savings to one minus the estate tax rate, typically about 0.09–0.16 (see Joulfaian, 2006 and Kopczuck and Slemrod, 2001), which also imply less elastic responses of capital.

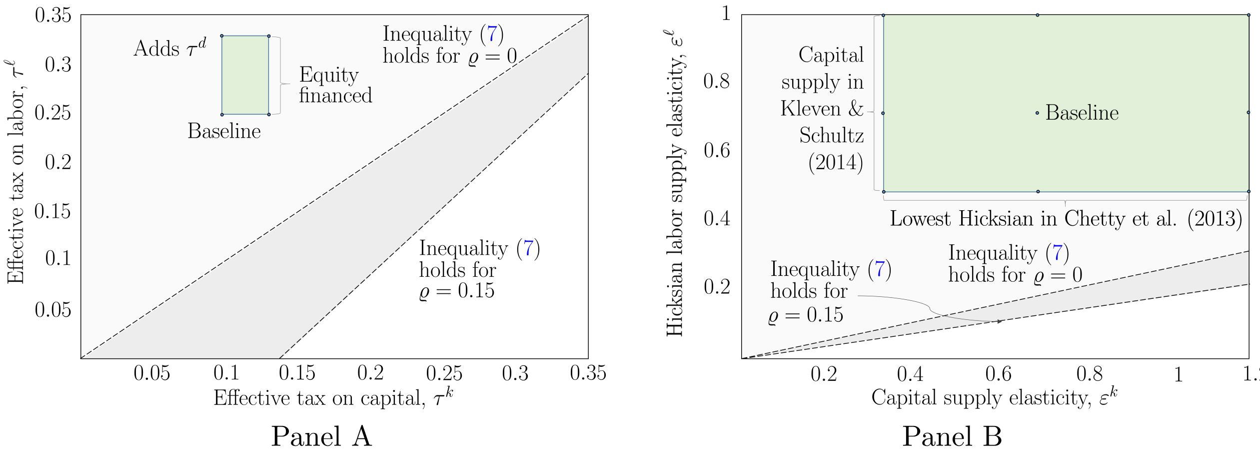


FIGURE 3: CONTOUR PLOTS OF TAXES AND ELASTICITIES THAT VERIFY INEQUALITY (9).
Notes: Panel A shows contour plots for estimates of the current US tax system and Panel B depicts contour plots for labor and capital supply elasticities to verify the robustness of the claim that the US tax system is biased against labor and in favor of capital. Green boxes represent the range of estimates we consider in our robustness checks and in each case we separately mark our baseline estimates. Inequality (9) is satisfied for $\varrho = 0$ in the light gray area and for $\varrho = 0.15$ in both the light and the dark gray areas. See the text for definitions and details.

ity (9) continues to be satisfied and the US tax system remains in the range where there is a bias against labor and in favor of capital. This is shown in Figure 3. Panel A of this figure documents that variations in how we compute effective taxes on capital and labor does not change this conclusion. It depicts two contour plots for τ^ℓ and τ^k that satisfy inequality (9) for the baseline values of the remaining parameters ($\varepsilon^\ell = 0.7; \varepsilon^k = 0.65$) and for $\varrho = 0.15$ (the solid line) and $\varrho = 0$ (the dotted line). All of our tax estimates lie within these sets and thus satisfy inequality (9) regardless of the value of ϱ. Panel B of Figure 3 turns to the question of whether this conclusion is robust to reasonable variations in the supply elasticities for capital and labor. It presents contour plots for the set of elasticities ε^ℓ and ε^k that satisfy inequality (9) for our baseline estimates of the US tax system ($\tau^\ell = 28.5\%; \tau^k = 9\%$), taking as given the benchmark values of the other parameters, and again separately for $\varrho = 0.15$ and $\varrho = 0$. Once more, the US tax system appears to satisfy inequality (9).

Consistent with this bias, the optimal taxes implied by Proposition 1 deviate significantly from the taxation of capital and labor in the US. Specifically, given our parameter choices, optimal (Ramsey) taxes are $\tau^{k,r} = 24.65\%$ and $\tau^{\ell,r} = 15.66\%$, which contrast with the observed taxes of $\tau^k = 10\%$ and $\tau^\ell = 25.5\%$. As anticipated previously, the reason why the optimal tax on labor is lower than on capital is because the supply elasticities for the two factors are similar, while there is an additional wedge for labor ($\varrho = 0.15$), which the optimal tax system corrects for.

4.3 The Implications of the US Tax System for Automation

We now return to our baseline parameters and investigate the implications of the US tax system for automation, employment, the labor share and welfare. As a first step, we compare the implied equilibrium level of automation under the tax system in the 2010s (before the 2017 tax reform), $\tau^{\ell} = 25.5\%$ and $\tau^{k} = 10\%$, to optimal taxes and automation, $\tau^{\ell,r} = 15.66\%$ and $\tau^{k,r} = 24.65\%$. The results of this comparison are presented in columns 1 and 2 of Table 1. Because the optimal tax system encourages the use of labor in production (relative to the US system in the 2010s), it would lead to a lower level of automation. Under the optimal tax system, θ declines to 0.167 from its equilibrium value in the 2010s, $\theta = 0.175$.[34] The lower level of automation under the optimal tax system would also increase the labor share by 0.53 percentage points and employment by 5.85%. Finally, welfare would be higher by 0.61% in consumption-equivalent terms (meaning that the welfare gains are equivalent to increasing consumption by 0.61%). Although this increase in welfare appears small (relative to the change in employment), this is for the usual intuition related to "Harberger triangles": because changes in welfare are second-order near the optimum, they tend to be smaller than changes in quantities unless we are very far away from this optimum. In fact, the welfare magnitudes here are sizable compared to those that are implied by other policies in similar settings.[35]

In Table 1, we used an effective tax rate on labor of $\tau^{\ell} = 25.5\%$, which does not include the additional implicit tax on labor implied by means-tested programs. Table A.1 in the Appendix shows that when we incorporate this additional implicit tax on labor supply and set $\tau^{\ell} = 33.5\%$, then the employment and welfare gains from changing the current system are amplified. Moving to optimal taxes now increases employment by 8.65%, the labor share by 0.73 percentage points and welfare by 1.2%.

Our main conclusion—that the we can raise welfare through tax reforms that raise employment and reduce automation—is robust to the variations in parameters and the measurement of taxes we presented in the previous subsection. Figure 4 considers the same range of taxes and parameters as in the two panels of Figure 3. The contours in this figure correspond to combinations of current tax rates (Panel A) and elasticities (Panel B) that give the same employment response when we switch from the current tax system to optimal taxes. The figure shows that for a wide range of parameters, the optimal tax system involves

[34] Though the quantitative magnitude of a change in θ is difficult to interpret, we can compute the share of employment that would be displaced with the higher level of θ. Given our parameter choices (in particular, $\psi^{\ell}(x)$ and $\psi^{k}(x)$), the decline in θ from 0.175 to 0.167 is equivalent to 3% fewer workers being displaced due to automation.

[35] For example,

Table 1: Equilibrium under the current tax system and under other potential scenarios.

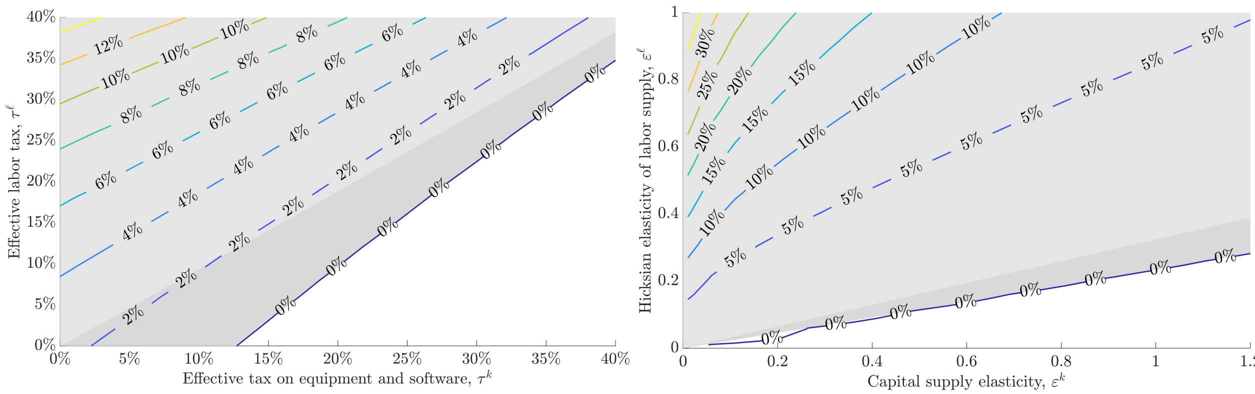
	Current System	Ramsey Solution	Distorting θ	Distorting θ and changing τ^k	Distorting θ and changing τ^ℓ
	(1)	(2)	(3)	(4)	(5)
Tax system:					
τ^k	10.00%	24.65%	10.00%	8.89%	10.00%
τ^ℓ	25.50%	15.66%	25.50%	25.50%	24.78%
θ	17.49%	16.71%	16.87%	16.75%	16.66%
τ^A	0.00%	0.00%	12.85%	15.62%	16.39%
Aggregates:					
Employment	.	+5.85%	+1.35%	+1.75%	+2.31%
Labor Share	60.00%	60.53%	62.06%	62.51%	62.68%
Output	.	+0.52%	−0.10%	+0.14%	+0.20%
C.E. welfare change	.	0.61%	0.12%	0.17%	0.23%
Revenue	.	0.00%	+1.54%	0.00%	0.00%

Notes: This table shows the effective capital and labor taxes, the level of automation and the automation tax under different scenarios. It also presents the implied changes in employment, aggregate output, welfare, and government revenue, and the level of labor share in national income. The first column is for the current US tax system. The second column shows the unconstrained Ramsey solution. Column 3 considers the implications of changing the level of automation, θ, with automation taxes (and no other change in policy). Column 4 additionally allows a change in the effective tax on capital, and column 5 considers a change in the effective tax on labor. Change in welfare is in terms of consumption equivalent. See the text for definitions and details.

levels of employment that are 2 to 10% larger than in the current system.

Recall from Proposition 2 that, when the tax system is biased against labor, the level of automation is not only greater than the Ramsey solution, but it is also excessively high compared to what would be socially optimal *given* the current tax system. Column 3 verifies that this is the case for our benchmark parameters and presents the level of automation that would maximize welfare taking the current system as given.[36] The level of automation that maximizes welfare is again around $\theta = 0.169$. In line with Proposition 4, this lower level of automation can be implemented with an automation tax of 12.85%—an additional tax on capital in marginal tasks around the market equilibrium $\theta^m(k,\ell)$. This automation tax implies that a task will be automated only if replacing labor with capital reduces the cost of

[36]The alternative is to follow Proposition 2 and look at the sum of the representative household's utility plus the change in revenue valued at μ (which is the social value of government funds in terms of units of consumption). Here, we simply look at the representative household's utility to make the results in this column comparable to the rest of the table. In any case, valuing additional revenues with the multiplier μ does not appreciably change our conclusions and simply leads to somewhat larger reductions in θ.



Panel A Panel B

FIGURE 4: CONTOUR PLOTS FOR THE PERCENT CHANGE IN EMPLOYMENT RESULTING FROM A MOVE FROM THE CURRENT TAX SYSTEM TO THE OPTIMAL TAX SYSTEM.
Notes: Panel A is for different combinations of estimates for the current US tax system, and Panel B is for different combinations of estimates of labor and capital supply elasticities. See the text for definitions and details.

producing that task by more than 12.85%. This automation tax improves welfare because it corrects for the inefficiently inflated price of labor under the current tax system. Specifically, it raises employment by 1.35% and the labor share by 2.06 percentage points. Even though equilibrium automation decisions are being distorted, aggregate output remains essentially unchanged (it declines by 0.10%). This is because, as already noted, marginal tasks that are automated under a distorted tax system do not increase productivity much or at all (or the automation technology being used in these tasks is "so-so" in the terminology of Acemoglu & Restrepo, 2019a).

Column 3 allows the planner to change θ, but without modifying the effective tax on capital, τ^k. We next verify that, as predicted by Proposition 3, if the planner can additionally modify τ^k (but cannot reduce labor taxes), she would still prefer to reduce automation starting from the current US tax system. This is illustrated in column 4, which shows that in this case the planner prefers to cut capital taxes to $\tau^k = 8.9\%$ and simultaneously impose a higher automation tax of 15.62%, again reducing θ to 0.167. This alternative tax system would lead to a 2.51 percentage points higher labor share and 1.75% more employment.

Finally, column 5 studies a setting where the planner can reduce taxes on labor and distort θ, but cannot increase taxes on capital (as mentioned above, this scenario may be relevant because of political constraints or fear of capital flight). In this case, the planner would impose a tax of 16.4% on automation, reducing automation again to about $\theta = 0.167$, which would increase employment by 2.31% and the labor share by 2.68 percentage points.[37]

[37]Importantly, this can be implemented without raising *any* capital taxes. In particular, a tax on automa-

In summary, our quantitative results show that the market equilibrium under the current tax system inefficiently favors automation. Reducing automation, with or without accompanying changes in other taxes, would increase employment significantly (by 1.35–5.85% depending on the experiment) and also raise the labor share in national income (by 0.53–2.68 percentage points).

4.4 Recent Reforms and Effective Stimulus

As described in footnote 18, a series of reforms enacted between the year 2000 and the mid 2010s significantly reduced effective taxes on equipment and software (from about 20% in the year 2000 to about 10%). The tax reform of 2017, which came into effect in 2018, further reduced effective taxes on equipment and software to about 5%. These reforms aimed to raise employment by stimulating investment and overall economic activity. In this subsection, we use our calibrated model to study the effectiveness of these reforms and their implications for automation. Our main finding is that, although all of these reforms increased employment (because they reduced effective taxes), their effects were fairly limited and they generated large fiscal costs per job created as they encouraged additional (excessive) automation. In contrast, we show that alternative reforms reducing labor taxes or combining subsidies to capital with an automation tax could have increased employment by a larger amount and cost the same revenue.

Column 1 of Table 2 reports the market equilibrium for the capital and labor taxes in 2000—$\tau^\ell = 25.5\%$ and $\tau^k = 20\%$. Column 2 then documents the impact of the tax cuts on capital enacted between 2000 and the mid 2010s, which lowered the effective tax on software and equipment to 10%. Our model implies that these tax cuts raised employment by a modest 1.15%, but did so at a large fiscal cost of $198,450 per job. In fact, our estimates suggest that these tax cuts reduced government revenue by 14.6%. As our theoretical analysis suggests, the lackluster employment response was in part because the lower taxes on capital encouraged greater automation, as shown by the increase in θ. Column 3 turns to the most recent (2017) tax cuts on capital. These are predicted to reduce government revenue by a an additional 7.83% (or 22.43% relative to the revenue collected in 2000) and encourage further automation, with θ rising to 0.176. The resulting employment gain is again small, 1.68% relative to 2000 (or 0.53% relative to the mid-2010s) and had a fiscal cost per job created of $208,619.

tion can also be implemented via a subsidy to labor of $\tau^A = 16.4\%$ and a tax on labor intensive tasks of τ^A for tasks above $\theta^c = 0.167$. This alternative implementation is discussed in Proposition A.1 in the Appendix, which generalizes Proposition 4.

Table 2: Comparison of observed tax reforms and reforms costing the same revenue.

		Observed reforms		Alternative reforms		
	System in 2000 with τ^k = 20%	System in 2010s: reform to τ^k = 10%	System in 2018: reform to τ^k = 5%	Labor tax reform	Capital tax reform with automation taxation	Capital and labor tax reform
	(1)	(2)	(3)	(4)	(5)	(6)
Tax system:						
τ^k	20.00%	10.00%	5.00%	20.00%	9.24%	24.65%
τ^ℓ	25.50%	25.50%	25.50%	18.67%	25.50%	15.66%
θ	17.19%	17.49%	17.63%	16.95%	16.99%	16.71%
τ^A	0.00%	0.00%	0.00%	0.00%	10.75%	0.00%
Aggregates:						
Employment	1	+1.15%	+1.68%	+5.37%	+2.38%	+7.06%
Capital	1	+6.24%	+9.25%	+1.29%	+4.87%	−1.26%
Labor Share	60.20%	60.00%	59.90%	60.36%	61.69%	60.53%
Output	1	+3.15%	+4.64%	+3.73%	+3.32%	+3.69%
Cost/Revenue per job ($)	.	$198,450	$208,619	$42,393	$95,904	$32,214
Revenue	.	−14.60%	−22.43%	−14.60%	−14.60%	−14.60%

Notes: This table shows the effective capital and labor taxes, the level of automation and subsidy to inframarginal tasks under different scenarios. Column 1 presents the equilibrium under the tax system of the year 2000. Columns 2 and 3 present the resulting changes from the capital tax cuts enacted up to the mid 2010s and then the subsequent capital tax cuts enacted in 2017. Columns 4–6 then show the effects of three alternative reforms that would have cost the same as the capital tax cuts enacted between 2000 and the mid 2010s. Column 4 considers cutting the effective labor tax. Column 5 considers a combination of capital tax cuts and a tax to automation. Column 6 considers a combination of lower labor taxes and higher capital taxes.

Columns 4-6 turn to alternative tax reforms that would have cost the same revenue as the capital tax cuts implemented between 2000 and the mid-2010s (14.6% of the year 2000 revenue). In column 4, we consider the implications of reducing labor taxes (for example, with a payroll tax cut) to $\tau^\ell = 18.67\%$ and keeping $\tau^k = 20\%$ as in 2000. This alternative reform would have increased employment by much more—by 5.37%—and would have cost only about 1/5th of the cost of one additional job in column 2. Part of the reason why reducing payroll taxes is much more effective in stimulating employment than cutting capital taxes is that lower payroll taxes reduce automation (θ falls to 0.169) whereas lower capital taxes further increase automation that is already excessively high (θ increases from 0.172 to 0.175 between columns 1 and 2).

Column 5 considers another reform, this time combining lower capital taxes with an automation tax (again chosen to cost the same revenue as the tax cuts enacted between 2000 and the mid 2010s). This reform would have also stimulated employment more than the reforms of the 2010s, increasing it by 2.38%, and would have cost $95,904 her job, which is about half the cost per job in column 2. Interestingly, this policy combination involves a larger tax cut for capital of 10.76%, but crucially it simultaneously rolls back excessive automation.[38]

Finally, column 6 considers another reform that changes both capital and labor taxes in a welfare maximizing way and costs the same revenue as the reform in column 2. By definition, this reform coincides with the Ramsey solution in column 2 of Table 1 and would have increased the effective capital tax rates to 27.1%, while reducing the labor tax to 16.3% (eliminating the payroll tax almost entirely). We include it in this table to show that, in addition to the 7.06% additional increase in employment, such a reform directly tackling the high labor taxes would have had a much smaller cost per job—only $32,214, or about 1/7th of the cost per job generated by the capital tax cuts since 2000.

Overall, this discussion reiterates that, because automation responds to the cost of capital and causes displacement of workers, reducing capital taxes uniformly and raising depreciation allowances is not an effective way of stimulating employment. Tax reforms over the last two decades or so that have reduced the effective tax on capital have only modestly increased employment and instead encouraged further automation. Reducing labor taxes or accompanying tax cuts for capital with a tax on automation can instead achieve greater increases in employment at much lower fiscal costs per job.

4.5 Capital Distortions

Our analysis so far incorporates labor market imperfections, via the labor market wedge ϱ, but ignores capital distortions. This is motivated by two considerations. First, our starting point is that, because of labor market imperfections such as bargaining, search or efficiency wages, even without any taxes, the level of employment would be too low; the baseline labor market friction introduces this property in a simple way. Second, while earning losses from worker displacement provide a natural way of identifying the labor market wedge, there is no simple way of ascertaining whether there are capital wedges and how large they may be.[39] Nevertheless, we have carried out a number of exercises to verify that our qualitative

[38]Note that a policy of reducing taxes on capital and at the same time taxing automation is equivalent to lowering the tax on capital by 10.76%, but only at tasks below $\theta = 0.17$. This exceeds the 10% tax cut from 2000 to the 2010s. These targeted tax cuts for capital at tasks in which it has a strong comparative advantage thus allow policy makers to give even larger subsidies to capital accumulation without triggering excessive automation.

[39]For example, large corporations that have significant cash at hand should not be using a different internal versus external rate of return, and their behavior should not be affected by a capital wedge, even if they use external funds. Smaller corporations may face a higher rate of return when borrowing funds, but if investment in these and larger corporations are highly substitutable, this may not correspond to an aggregate capital wedge.

and quantitative conclusions are not unduly affected by this asymmetry in the treatment of capital and labor.

First, we show in the Appendix that if equity finance is not subject to an additional distortion, then the deductions of interest rate payments from taxes in the case of debt finance more than undo any capital market distortions. Intuitively, the interest rate on corporate loans is an upper bound on the capital wedge and is deducted from taxes. Therefore, we can conservatively use effective tax rates on equipment and software that would apply only with full equity financing (without any of the reductions in effective capital taxes given by debt finance). Table A.2 in the Appendix provides analogous results to Table 1 in this case. The effective capital taxes are now $\tau^k = 12\%$ but this has minimal effects on our results. Second, Table A.3 in the Appendix repeats our main exercise but now assuming a capital wedge of $\varrho^k = 0.15$—the same as the labor wedge. The employment and welfare gains from moving to optimal taxes are still non-trivial even if about half as large as our baseline estimates. Overall, we conclude that our results are not driven by the assumption that there are no capital wedges or the asymmetric treatment of capital and labor.

5 Extensions

In this section, we discuss several extensions that generalize our model in more realistic directions and further reinforce our main conclusionsmeaning that the US tax code favors capital and promotes excessive automation.

5.1 Human Capital Investments

The asymmetric treatment of capital and labor may further distort investments in human capital. This, in turn, may interact with automation decisions. A range of new issues arise when considering human capital investments. In this context, three different types of human capital investments may need to be considered: (1) general human capital investments via schooling (where, following Becker, 1964, by "general", we mean human capital that increases the productivity of the worker with a range of employers); (2) general human capital investments undertaken on the job (via training); (3) specific human capital investments undertaken on the job, which are relevant only with the current employer. The implications of each one of these three types of investments (and mixtures thereof) are different. Here, for simplicity, we focus on general human capital investments, without distinguishing schooling from training.

Suppose that the effective labor services provided by the worker is augmented by human capital denoted by h. Assume also that all workers will have the same amount of human capital, so that the effective labor services of workers are now $\ell^h = h \cdot \ell$.[40] The cost of investing in human capital h for ℓ workers is $\frac{\ell}{1+1/\varepsilon^h} \cdot h^{1+1/\varepsilon^h}$ in terms of the final good of the economy, and $\varepsilon^h > 0$. This parameter will be the elasticity of investment in human capital with respect to changes in wages. Likewise, we take the iso-elastic specification of $\nu(\ell)$ and $\phi(k)$ used in our quantitative section, so that ε^ℓ is the constant Hicksian elasticity of the labor supply and ε^k the capital supply elasticity.

Incorporating human capital into the labor market clearing condition, we obtain

$$f_{\ell^h} \cdot (1 - \tau^\ell) \cdot (1 - \varrho) = \ell^{h^{1/(\varepsilon^\ell + \varepsilon^h + \varepsilon^\ell \cdot \varepsilon^h)}}.$$

The relevant elasticity for the supply of effective labor has now been replaced by $\varepsilon^\ell + \varepsilon^h + \varepsilon^\ell \cdot \varepsilon^h$, which incorporates the elastic response of human capital and is thus always greater than ε^ℓ. Intuitively, effective labor services can be increased not just by supplying labor, but by investing in human capital as well.

The next proposition characterizes optimal taxes in the presence of human capital and shows that labor taxes need to be adjusted to take into account the greater elasticity with which labor services respond to taxation. This pushes in the direction of (relatively) lower labor taxes, and conversely, higher capital taxes.

PROPOSITION 5 ***(Optimal taxes with endogenous human capital)*** *The solution to the Ramsey problem in this extended environment with human capital satisfies $\theta^r = \theta^m(k, \ell)$ and*

$$\frac{\tau^{k,r}}{1 - \tau^{k,r}} = \frac{\mu}{1+\mu} \cdot \frac{1}{\varepsilon^k} \qquad \frac{\tau^{\ell,r}}{1 - \tau^{\ell,r}} = \frac{\mu}{1+\mu} \cdot \frac{1}{\varepsilon^\ell + \varepsilon^h + \varepsilon^\ell \varepsilon^h} - \frac{\varrho}{1+\mu}.$$

It is also straightforward to see that if an economy has too low a tax on capital and excessive automation without human capital (in the sense of Proposition 2), it will a fortiori have too low a tax on capital and excessive automation when there is an elastic response of human capital. Therefore, our (both theoretical and quantitative) conclusions so far are strengthened when we consider human capital investments.

We next provide a back of the envelope quantification of the extent of this effect. To do this, we only need to augment our analysis in the previous section with an estimate for the

[40] This formulation ignores the fact that high-human capital workers may be employed in tasks that are not automated or are complementary to automation technologies. The impact of automation on the employment and wages of different types of workers is explored in Autor, Levy & Murnane (2003) and Acemoglu & Restrepo (2020b).

elasticity of human capital, ε^h. We set the elasticity of human capital supply, ε^h, to 0.092. This value is in the mid-range of estimates from the literature on high-school completion (Jensen, 2010; Kuka et al., 2018) and college major choice (Wiswall & Zafar, 2015; Beffy et al., 2012).[41] This increases the elasticity of the effective labor supply to 0.86, and as a result, the optimal labor tax is now lower, $\tau^\ell = 14.02\%$, and the optimal capital tax is modestly higher, $\tau^k = 26.77\%$ (see Table A.6 in the Appendix). Consequently, replacing the current system with optimal taxes leads to more pronounced changes: 0.69 percentage point higher labor share, 8.11% increase in employment, and 0.9% increase in welfare in consumption-equivalent terms.

5.2 Endogenous Technology

In our baseline model, increases in θ represent both the development and the adoption of automation technologies. In principle, these two decisions are distinct, even if related. Unless automation technologies are developed, they cannot be adopted. If they are expected to be adopted, then there are greater incentives to develop them. More importantly, however, as emphasized in Acemoglu & Restrepo (2018), the development of automation technologies may come at the expense of other technological changes with very different implications for capital and labor. For instance, more resources devoted to automation typically implies less effort towards the introduction of new tasks that tend to increase the labor share and demand for labor. If so, a tax structure that favors capital and automation may also distort the direction of technological change in a way that disadvantages labor. In this subsection, we provide a simple model to highlight these ideas and investigate whether endogenous direction of technology provides an additional motive for higher taxes on capital and discouragement to automation.

For brevity, we borrow from the formulation of endogenous technology in Acemoglu (2007, 2010), whereby a (competitive) production sector decides how much capital and labor to use and which technology, from a menu of available technologies, to utilize, while a monopolistically competitive (or simply monopolistic) technology sector decides which technologies to develop and offer to firms.

[41] Jensen's (2010) experimental results imply that a 13% increase in high-school completion rates in response to a 134% increase in perceived returns, and corresponds to a 0.097 high-school completion elasticity. Kuka et al. (2018) estimate a high-school completion elasticity of 0.019-0.086 in response to actual returns, and 0.014-0.17 in response to perceived returns. These results imply a semi-elasticity of 0.25. Wiswall & Zafar (2015) estimate elasticities in the range of 0.036-0.062 from the response of college major choice to changes in relative wage premium. Previous estimates in Beffy et al. (2012) put the same elasticity in the range 0.09–0.12. Taken together, these studies imply human capital supply elasticities in the range 0.014–0.17.

Specifically, let $\tilde{\theta}$ denote the extent of automation in the technologies offered by the technology sector (namely that the tasks in $[0, \tilde{\theta}]$ can be automated), while, as before, θ denotes the automation decision of the production sector. The amount of final goods produced by the competitive production sector is

$$F(k, \ell; \theta, \tilde{\theta})$$

(provided that the level of automation is feasible, meaning that $\theta \leq \tilde{\theta}$). In addition, this production function satisfies the usual assumptions, and

$$F(k, \ell; \theta, \tilde{\theta} = \theta) = f(k, \ell; \theta),$$

where $f(k, \ell; \theta)$ is the production function depending on capital, labor and automation used in our benchmark model.

To capture the trade-offs modeled in Acemoglu & Restrepo (2018) in a reduced-form way, we next assume:

1. $F_k(k, \ell; \theta, \tilde{\theta})$ is increasing in $\tilde{\theta}$: this encodes the natural assumption that more advanced automation technologies increase the marginal product of capital.

2. $F_\ell(k, \ell; \theta, \tilde{\theta})$ is decreasing in $\tilde{\theta}$: this is the key aspect we borrow from Acemoglu & Restrepo (2018)—the more investment there is in automation technologies, the less there is for new tasks, and this reduces the marginal product of labor.

Finally, following Acemoglu (2007, 2010), we assume that the technology sector receives a fraction of the output of the final good sector (for example, by selling machines embedding the new technology with a constant markup) and has a cost that depends on the technology it produces, so that the maximization problem can be expressed as:

$$\tilde{\theta}^m(k, \ell, \theta) = \max_{\tilde{\theta} \in [0,1]} \kappa F(k, \ell; \theta, \tilde{\theta}) - \Gamma(\tilde{\theta}), \tag{20}$$

where $\kappa \in (0, 1)$ represents the fraction of the revenue generated by the final good sector captured by technology suppliers (in models with constant elasticity of substitution, this is a simple function of the elasticity of demand for machines embedding the new technology). In addition, $\Gamma(\tilde{\theta})$ is the cost function facing the technology sector. We make the following assumptions on $\Gamma(\tilde{\theta})$:

- $\Gamma(\tilde{\theta})$ is convex. This is natural and captures diminishing returns in research directed to any specific type of technology.

- $\Gamma(\tilde{\theta})$ has a minimum at $\bar{\theta} \in (0,1)$. This assumption means that there exists a baseline level of automation given by $\bar{\theta}$, and costs increase when the technology sector tries to deviate from this level. Deviations from $\bar{\theta}$ can come in the direction of further automation or further effort devoted to creating new tasks (and thus less automation). Both of these will be more costly than continuing with $\bar{\theta}$. In the dynamic framework of Acemoglu & Restrepo (2018), $\bar{\theta}$ corresponds to the state of technology inherited from the past.

Therefore, an equilibrium in this economy is the same as a competitive equilibrium in our benchmark economy augmented with $\tilde{\theta}^m(k,\ell,\theta)$ that solves (20) and a consistency requirement between adoption and development decisions, that is, $\theta^m(k,\ell;\tilde{\theta}) \leq \tilde{\theta}^m(k,\ell,\theta)$.

We next characterize the unconstrained Ramsey problem as in Proposition 1. In the spirit of Proposition 1 we assume that the planner can directly control both the adoption of automation technology and the development of automation technologies, and we compare the latter to the equilibrium choice of the technology sector, $\tilde{\theta}^m(k,\ell,\theta)$.

PROPOSITION 6 ***(Optimal taxes and automation with endogenous technology)*** *Consider the Ramsey problem in this extended environment with endogenous technology and suppose that the solution to this problem involves $\tilde{\theta}^r = \bar{\theta}$. Then we have $\theta^r = \theta^m(k,\ell,\tilde{\theta}^r) = \tilde{\theta}^r$, $\tilde{\theta}^r = \tilde{\theta}^m(k,\ell,\theta)$, and*

$$\frac{\tau^{k,r}}{1-\tau^{k,r}} = \frac{\mu}{1+\mu}\cdot\frac{1}{\varepsilon^k(k)} \qquad\qquad \frac{\tau^{\ell,r}}{1-\tau^{\ell,r}} = \frac{\mu}{1+\mu}\cdot\frac{1}{\varepsilon^\ell(\ell)} - \frac{\varrho}{1+\mu}. \tag{21}$$

However, if $\tilde{\theta}^r \lesseqgtr \bar{\theta}$, we still have $\theta^r = \theta^m(k,\ell,\tilde{\theta}^r) = \tilde{\theta}^r$ and (21), but crucially $\tilde{\theta}^r \lesseqgtr \tilde{\theta}^m(k,\ell,\theta^r)$.

The most important implication of this proposition is that, even in the unconstrained Ramsey problem, the planner might wish to tax or discourage the development of automation technology. This will be the case when the baseline level of technology is more geared towards automation than what the planner would like to achieve. Put differently, if the economy in question has already gone in the direction of excessively developing automation technologies (which may be a consequence of past distortions or other factors influencing the direction of past technological change), then the planner should intervene by distorting the direction of innovation. The reason for this is straightforward: the technology sector does not fully internalize the social surplus its technologies generate (because of the presence of the term $\kappa < 1$ in (20)), and thus will not develop the right type of technologies. This result has a close connection to one of the key insights in Acemoglu et al. (2012), which establishes, in the context of optimal climate change policy, that if the economy starts with relatively advanced carbon-emitting, dirty technologies and relatively backward low-carbon, clean technologies, then it is not sufficient to impose Pigouvian taxes; rather, optimal policy additionally calls for direct subsidies to the development of clean technologies.[42]

This result is important in our context, because, if as our results in Section 4 suggest, past US tax policy has favored capital and automation, then it is not sufficient to redress the distortions in the current tax system. Because these policies have likely led to excessive development of automation technologies, optimal policy may need to intervene to redirect technology by subsidizing the creation of new tasks and perhaps discouraging further effort towards automation technologies at the margin. We leave a quantitative exploration of the implications of endogenous technology development to future work.

5.3 Within-Task Capital-Labor Complementarity

We have so far assumed that within the task capital and labor are perfectly substitutable. In reality, workers may benefit from the use of capital in some labor-intensive tasks. We now capture this in a simple way by modifying the task-specific production function (1) to

$$y(x) = \psi^{\ell}(x) \cdot \ell(x)^{\alpha} \cdot \tilde{k}(x)^{1-\alpha} + \psi^{k}(x) \cdot k(x),$$

where $\tilde{k}(x)$ denotes the type of capital that is complementary to labor within tasks (different from $k(x)$ which corresponds to capital used for automating task x). The total amount of capital in the economy then becomes $k = \int_0^1 k(x)dx + \int_0^1 \tilde{k}(x)dx$. The results are very similar in this case, with the main difference being that there is now an added motive for subsidizing capital while taxing automationbecause this would increase $\tilde{k}(x)$ in tasks that are not automated.

6 Concluding Remarks

Automation is transforming labor markets and the structure of work in many economies around the world, not least in the United States. The number of robots in industrial applications, the use of specialized software, artificial intelligence and several other automation technologies have increased rapidly in the US economy over the last few decades. There has been a concomitant decline in the labor share of national income, wages have stagnated and low-skill workers have seen their real wages decline. Many experts believe that these trends are, at least in part, related to automation.

[42] Note in addition that in our setup, once the planner can influence the direction of automation technology and there are no other distortions, she has no need to distort the adoption of automation technologies.

The general intuition among economists (and many policy-makers) is that even if automation may come with some adverse distributional and employment consequences, policy should not slow down (and certainly not prevent) the adoption of automation technologies, because these technologies are contributing to productivity. Policy should, instead, focus on fiscal redistribution, education and training to ensure more equally-distributed gains and more opportunities for social mobility. But what if automation is excessive from a social point of view?

This paper has argued that the US tax system is likely to be encouraging excessive automation and if so, reducing the extent of automation (or more plausibly, slowing down the adoption of new automation technologies) may be welfare-improving. We have developed this argument in three steps.

First, we revisited the theory of optimal capital and labor taxation in a task-based framework where there is an explicit decision of firms to automate tasks and use capital instead of labor in their production. We also introduced, albeit in a reduced-form manner, labor market imperfections. Consistent with the classical theory of public finance, if capital and labor taxes are set optimally, then automation decisions are optimal in equilibrium. However, away from optimal capital and labor taxes or in the presence of additional constraints on tax decisions, this is no longer the case. Exploiting the structure of our task-based framework, we establish that when the tax system is already biased against labor, it is generally optimal to distort equilibrium automation. The economics of this result is simple but informative: marginal tasks that are automated bring little productivity gains (or in the terminology of Acemoglu & Restrepo, 2019a, they are "so-so automation technologies"), and as a result the cost of reducing automation at the margin is second-order. When the tax system is biased against labor, the gain from reducing automation and preventing its displacement of labor is first-order because it increases employment. In fact, it may even be optimal to reduce automation while at the same time increasing the capital stock in the economy (even though the tax system is biased against labor and in favor of capital), because, in contrast to automation, capital is complementary to labor and a greater capital stock tends to increase the marginal product of labor and thus employment.

Second, we delved into a detailed evaluation of the US tax system in order to map the complex tax code into effective capital and labor taxes. Our numbers suggest that the US tax system favors capital significantly. While labor is taxed at an effective rate between 25.5% and 33.5%, capital faces an effective tax rate of about 5% (down from 10% in the 2010s and 20% in the 1990s and early 2000s).

Third, we compared the US tax system to optimal taxes implied our theoretical analysis.

This exercise confirmed that the US tax system is strongly biased against labor and in favor of capital. As a result, we found that moving from the current US tax system and level of automation to optimal taxation of factors and the optimal level of automation would raise employment by 5.85%, the labor share by 0.53 percentage point and overall welfare by 0.61% in consumption-equivalent terms. If moving to optimal policy is not feasible, more modest reforms involving a tax on automation can still increase employment by 1.35–2.31% and the labor share by 2.06–2.68 percentage points.

We also showed that a range of realistic generalizations (absent from our baseline framework) reinforce our conclusions and call for even more extensive changes in automation and capital taxation.

To simplify the analysis and for parsimony, we focused on an economy with a single type of labor. As noted in the Introduction, automation is also associated with increases inequality (Autor, Levy & Murnane, 2003; Acemoglu & Autor, 2011; Acemoglu & Restrepo, 2020a,b). Consequently, slowing down automation may generate additional benefits by reducing inequality. These issues are discussed in Guerreiro, Rebelo & Teles (2017), Thuemmel (2018) and Costinot & Werning (2018). A natural next step is to augment these analysis with the possibility that other aspects of the tax system may be encouraging excessive automation, and it is straightforward but still interesting to use estimates on the effects of automation technologies on inequality (e.g., from Acemoglu & Restrepo, 2020b) to evaluate the impact of excessive automation on the rise in US inequality.

In practice, there are many reasons why there may be excessive automation. Our objective in this paper has been narrow: to focus on tax reasons for excessive automation. Our companion paper Acemoglu, Manera & Restrepo (2020) shows that, even absent tax-related distortions, the market economy tends to generate excessive automation because bargaining power and efficiency wage considerations vary across tasks and this tends to create incentives for firms to automate beyond what is socially beneficial. As we have already noted, automation-driven job loss may generate negative spillovers on communities and political and social behavior. There may additionally be social factors and norms (what individuals and companies view as the most exciting types of applications) and reasons related to the direction of innovation and research (the best minds in many important fields working on automation technologies) that further contribute to excessive automation. The extent of these other factors is an interesting and important area for future research, especially because they have major implications for policy.

Finally, we should note that though our framework suggests it may be beneficial to increase taxes on capital, wealth taxes on high wealth individuals may not be the most direct way of achieving this, because they would not necessarily increase the effective tax on the use of capital. Increasing corporate income taxes and eliminating or lowering depreciation allowances may be more straightforward ways of implementing higher effective taxes on capital (provided that there are no other distributional or political benefits from wealth taxes). Moreover, our framework emphasizes that it is often equally or more important to reduce excessive automation, not just tax capital.

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Appendix:

Does the US Tax Code Favor Automation?
Acemoglu, Manera, Restrepo

A.1 Robustness Checks and Additional Figures Discussed in the Main Text

This part of the Appendix presents the following additional results and robustness checks discussed in the main text:

- Figure A.1 provides the time-series of the total value of depreciation allowances by type of capital, α^j, and compares this to the allowance that would result from economic depreciation. Each figure presents a single average across the types of assets included in each category (software, equipment and non-residential structures).
- Figure A.2 presents the evolution of effective taxes on capital when all investment is financed with equity. For comparison, we also show the effective tax on labor.
- In Table A.1 we additionally include the implicit tax on labor implied by means-tested programs. With this higher effective tax on labor (equal to 33.5%), there are greater employment and welfare gains from moving towards optimal taxes and lower estimation.
- Table A.2 is the analogue of Table 1 when the effective tax on capital is based on full equity financing. This leads to somewhat lower employment and welfare gains from moving to optimal taxes.
- Table A.3 presents a version of Table 1 when there is a 15% wedge for capital. This leads to employment and welfare gains that are approximately half as large as those in Table 1.
- In Table A.4 we use only the extensive margin elasticity of labor supply. This also reduces employment and welfare gains significantly, but they still remain positive.
- In Table A.5 we set $\upsilon = 0$, so that labor has an absolute disadvantage in tasks where it has a comparative advantage. In this case, employment and welfare gains are significantly larger.

- Table A.6 follows our extension in Section 5.1 by adding the endogenous response of human capital to the elasticity of labor supply. This leads to significantly larger employment and welfare gains from moving towards optimal taxes.
- In Table A.7 sets $\varepsilon^k = 1$. This leads to employment and welfare gains that are about half as large as in our baseline in Table 1.

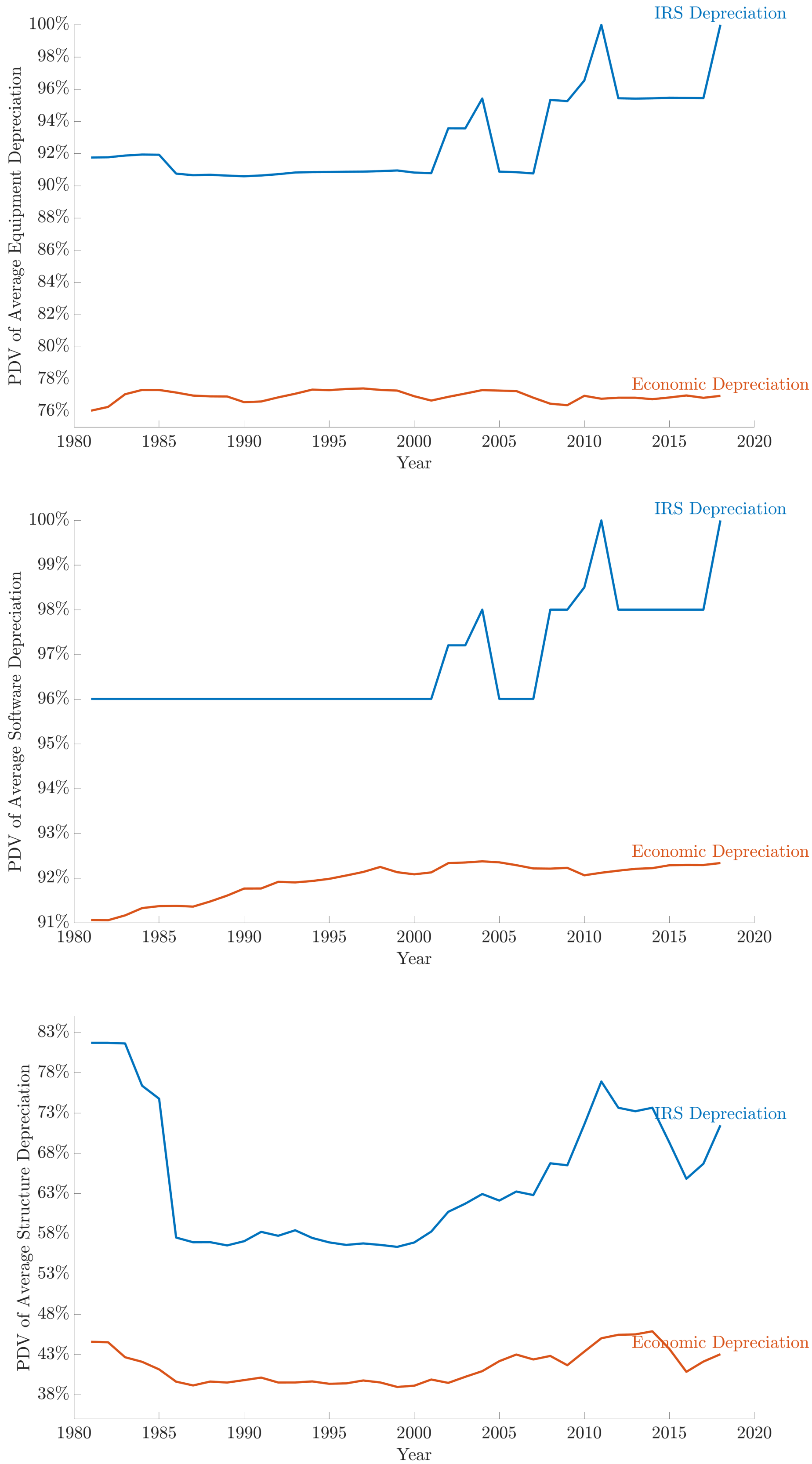

FIGURE A.1: ESTIMATED DEPRECIATION ALLOWANCES OVER TIME FOR EQUIPMENT, SOFTWARE AND NON-RESIDENTIAL STRUCTURES.

Notes: See the text for definitions.

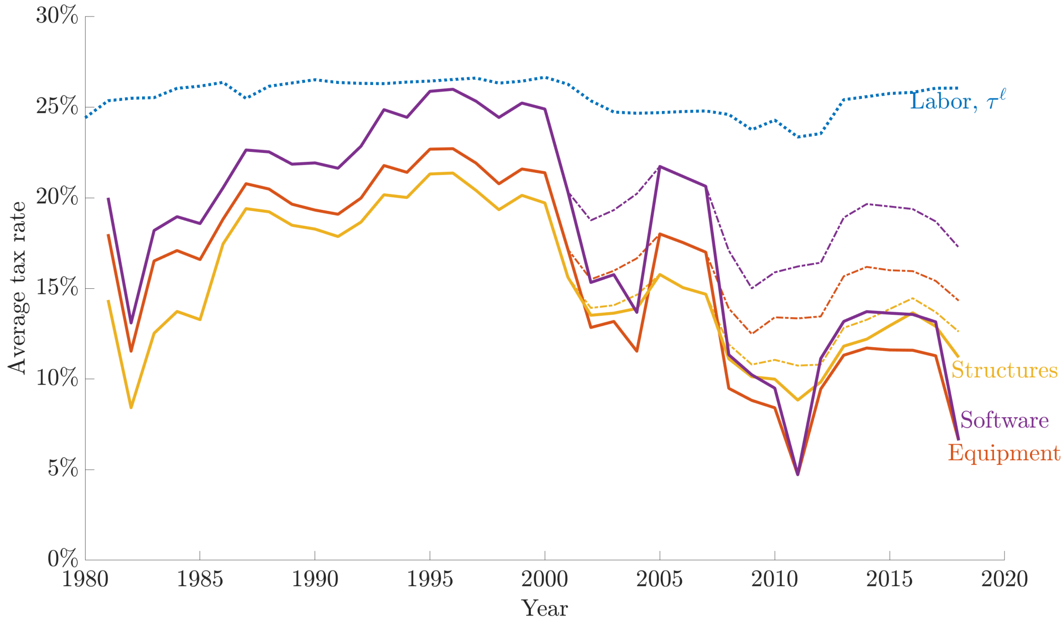

FIGURE A.2: EFFECTIVE TAX RATES ON LABOR, SOFTWARE CAPITAL, EQUIPMENT, AND NON-RESIDENTIAL STRUCTURES WITH EQUITY FINANCING.

Notes: The alternative series for the effective tax rate on labor includes the phase out of means tested programs. See the text for definitions and sources.

TABLE A.1: Robustness: including the implicit tax on labor from means-tested and disability programs.

	Current System	Ramsey Solution	Distorting θ	Distorting θ and changing τ^k	Distorting θ and changing τ^ℓ
	(1)	(2)	(3)	(4)	(5)
Tax system:					
τ^k	10.00%	28.51%	10.00%	7.70%	10.00%
τ^ℓ	33.50%	20.59%	33.50%	33.50%	31.94%
θ	18.00%	16.91%	17.22%	17.03%	16.81%
τ^A	0.00%	0.00%	15.40%	20.03%	21.58%
Aggregates:					
Employment	.	+8.71%	+1.64%	+2.37%	+3.71%
Labor Share	59.70%	60.43%	62.21%	63.00%	63.37%
Output	.	+1.32%	−0.17%	+0.32%	+0.55%
C.E. welfare change	.	1.19%	0.18%	0.30%	0.50%
Revenue	.	0.00%	+2.28%	0.00%	0.00%

Notes: This table shows the effective capital and labor taxes, the level of automation and the automation tax under different scenarios. It also presents the implied changes in employment, aggregate output, welfare, and government revenue, and the level of labor share in national income. The first column is for the current US tax system. The second column shows the unconstrained Ramsey solution. Column 3 considers the implications of changing the level of automation, θ, with automation taxes (and no other change in policy). Column 4 additionally allows a change in the effective tax on capital, and column 5 considers a change in the effective tax on labor. Change in welfare is in terms of consumption equivalent. See the text for definitions and details.

Table A.2: Robustness: effective tax on capital for equity financing only

	Current System	Ramsey Solution	Distorting θ	Distorting θ and changing τ^k	Distorting θ and changing τ^ℓ
	(1)	(2)	(3)	(4)	(5)
Tax system:					
τ^k	12.00%	25.34%	12.00%	11.10%	12.00%
τ^ℓ	25.50%	16.55%	25.50%	25.50%	24.92%
θ	17.33%	16.61%	16.75%	16.65%	16.57%
τ^A	0.00%	0.00%	12.02%	14.55%	15.15%
Aggregates:					
Employment	.	+5.31%	+1.27%	+1.61%	+2.06%
Labor Share	60.00%	60.48%	61.91%	62.32%	62.46%
Output	.	+0.42%	−0.09%	+0.11%	+0.16%
C.E. welfare change	.	0.52%	0.10%	0.15%	0.20%
Revenue	.	0.00%	+1.20%	0.00%	0.00%

Notes: This table shows the effective capital and labor taxes, the level of automation and the automation tax under different scenarios. It also presents the implied changes in employment, aggregate output, welfare, and government revenue, and the level of labor share in national income. The first column is for the current US tax system. The second column shows the unconstrained Ramsey solution. Column 3 considers the implications of changing the level of automation, θ, with automation taxes (and no other change in policy). Column 4 additionally allows a change in the effective tax on capital, and column 5 considers a change in the effective tax on labor. Change in welfare is in terms of consumption equivalent. See the text for definitions and details.

Table A.3: Robustness: capital wedge of 15%

	Current System	Ramsey Solution	Distorting θ	Distorting θ and changing τ^k	Distorting θ and changing τ^ℓ
	(1)	(2)	(3)	(4)	(5)
Tax system:					
τ^k	10.00%	20.23%	10.00%	9.16%	9.99%
τ^ℓ	25.50%	18.52%	25.50%	25.53%	24.97%
θ	17.50%	16.95%	17.16%	16.99%	16.91%
τ^A	0.00%	0.00%	7.07%	11.06%	11.69%
Aggregates:					
Employment	.	+4.26%	+0.75%	+1.23%	+1.66%
Labor Share	60.00%	60.37%	61.10%	61.74%	61.87%
Output	.	+0.56%	−0.01%	+0.16%	+0.22%
C.E. welfare change	.	0.30%	0.03%	0.08%	0.12%
Revenue	.	+0.03%	+0.87%	+0.00%	+0.01%

Notes: This table shows the effective capital and labor taxes, the level of automation and the automation tax under different scenarios. It also presents the implied changes in employment, aggregate output, welfare, and government revenue, and the level of labor share in national income. The first column is for the current US tax system. The second column shows the unconstrained Ramsey solution. Column 3 considers the implications of changing the level of automation, θ, with automation taxes (and no other change in policy). Column 4 additionally allows a change in the effective tax on capital, and column 5 considers a change in the effective tax on labor. Change in welfare is in terms of consumption equivalent. See the text for definitions and details.

Table A.4: Robustness: using the extensive-margin Hicksian elasticity for the labor supply

	Current System (1)	Ramsey Solution (2)	Distorting θ (3)	Distorting θ and changing τ^k (4)	Distorting θ and changing τ^ℓ (5)
Tax system:					
τ^k	10.00%	17.96%	10.00%	9.60%	10.00%
τ^ℓ	25.50%	20.38%	25.50%	25.50%	25.25%
θ	16.16%	15.83%	15.91%	15.85%	15.82%
τ^A	0.00%	0.00%	6.01%	7.70%	8.12%
Aggregates:					
Employment	.	+1.74%	+0.35%	+0.46%	+0.59%
Labor Share	60.00%	60.21%	60.90%	61.16%	61.24%
Output	.	–0.59%	–0.19%	–0.16%	–0.20%
C.E. welfare change	.	0.13%	0.02%	0.03%	0.04%
Revenue	.	0.00%	+0.53%	0.00%	0.00%

Notes: This table shows the effective capital and labor taxes, the level of automation and the automation tax under different scenarios. It also presents the implied changes in employment, aggregate output, welfare, and government revenue, and the level of labor share in national income. The first column is for the current US tax system. The second column shows the unconstrained Ramsey solution. Column 3 considers the implications of changing the level of automation, θ, with automation taxes (and no other change in policy). Column 4 additionally allows a change in the effective tax on capital, and column 5 considers a change in the effective tax on labor. Change in welfare is in terms of consumption equivalent. See the text for definitions and details.

Table A.5: Robustness: assuming labor has an absolute disadvantage at higher-indexed tasks

	Current System	Ramsey Solution	Distorting θ	Distorting θ and changing τ^k	Distorting θ and changing τ^ℓ
	(1)	(2)	(3)	(4)	(5)
Tax system:					
τ^k	10.00%	24.71%	10.00%	8.43%	10.00%
τ^ℓ	25.50%	15.73%	25.50%	25.50%	24.52%
θ	65.66%	64.22%	64.52%	64.31%	64.13%
τ^A	0.00%	0.00%	12.83%	15.82%	16.20%
Aggregates:					
Employment	.	+6.55%	+1.85%	+2.41%	+3.15%
Labor Share	60.00%	61.51%	62.82%	63.44%	63.68%
Output	.	+0.59%	−0.14%	+0.20%	+0.28%
C.E. welfare change	.	0.69%	0.16%	0.24%	0.32%
Revenue	.	0.00%	+2.12%	0.00%	0.00%

Notes: This table shows the effective capital and labor taxes, the level of automation and the automation tax under different scenarios. It also presents the implied changes in employment, aggregate output, welfare, and government revenue, and the level of labor share in national income. The first column is for the current US tax system. The second column shows the unconstrained Ramsey solution. Column 3 considers the implications of changing the level of automation, θ, with automation taxes (and no other change in policy). Column 4 additionally allows a change in the effective tax on capital, and column 5 considers a change in the effective tax on labor. Change in welfare is in terms of consumption equivalent. See the text for definitions and details.

Table A.6: Robustness: accounting for human capital responses

	Current System	Ramsey Solution	Distorting θ	Distorting θ and changing τ^k	Distorting θ and changing τ^ℓ
	(1)	(2)	(3)	(4)	(5)
Tax system:					
τ^k	10.00%	26.77%	10.00%	8.50%	10.00%
τ^ℓ	25.50%	14.02%	25.50%	25.50%	24.53%
θ	18.03%	17.03%	17.22%	17.09%	16.97%
τ^A	0.00%	0.00%	15.41%	18.47%	19.10%
Aggregates:					
Employment	.	+8.11%	+1.95%	+2.50%	+3.35%
Labor Share	60.00%	60.69%	62.55%	63.06%	63.23%
Output	.	+1.45%	+0.04%	+0.42%	+0.60%
C.E. welfare change	.	0.90%	0.18%	0.26%	0.37%
Revenue	.	0.00%	+2.08%	0.00%	0.00%

Notes: This table shows the effective capital and labor taxes, the level of automation and the automation tax under different scenarios. It also presents the implied changes in employment, aggregate output, welfare, and government revenue, and the level of labor share in national income. The first column is for the current US tax system. The second column shows the unconstrained Ramsey solution. Column 3 considers the implications of changing the level of automation, θ, with automation taxes (and no other change in policy). Column 4 additionally allows a change in the effective tax on capital, and column 5 considers a change in the effective tax on labor. Change in welfare is in terms of consumption equivalent. See the text for definitions and details.

Table A.7: Robustness: setting $\epsilon^k = 1$

	Current System	Ramsey Solution	Distorting θ	Distorting θ and changing τ^k	Distorting θ and changing τ^ℓ
	(1)	(2)	(3)	(4)	(5)
Tax system:					
τ^k	10.00%	19.72%	10.00%	9.35%	9.94%
τ^ℓ	25.50%	19.21%	25.50%	25.50%	25.14%
θ	16.15%	15.61%	15.74%	15.63%	15.58%
τ^A	0.00%	0.00%	8.92%	11.62%	12.02%
Aggregates:					
Employment	.	+3.42%	+0.82%	+1.15%	+1.40%
Labor Share	60.00%	60.36%	61.39%	61.81%	61.90%
Output	.	−0.54%	−0.30%	−0.18%	−0.22%
C.E. welfare change	.	0.30%	0.06%	0.10%	0.12%
Revenue	.	0.00%	+0.81%	0.00%	0.00%

Notes: This table shows the effective capital and labor taxes, the level of automation and the automation tax under different scenarios. It also presents the implied changes in employment, aggregate output, welfare, and government revenue, and the level of labor share in national income. The first column is for the current US tax system. The second column shows the unconstrained Ramsey solution. Column 3 considers the implications of changing the level of automation, θ, with automation taxes (and no other change in policy). Column 4 additionally allows a change in the effective tax on capital, and column 5 considers a change in the effective tax on labor. Change in welfare is in terms of consumption equivalent. See the text for definitions and details.

A.2 Derivations and Proofs for the Static Model

This part of the Appendix presents the proofs of the results stated in the text and some additional results briefly mentioned in the text.

Characterization of the Equilibrium and the Ramsey Problem

The next lemma provides the characterization of the competitive equilibrium presented in the text and is the basis of all subsequent proofs.

Lemma 1 (Equilibrium characterization) *Given a tax system* (τ^k, τ^ℓ) *and a labor wedge* ϱ*, a market equilibrium is given by an allocation* $\{k, \ell\}$ *and a threshold task* θ *such that:*

- *aggregate output* y *is given by* $f(k, \ell; \theta)$ *in (2);*
- $\theta = \theta^m(k, \ell)$ *maximizes* $f(k, \ell; \theta)$*;*
- *the capital- and labor-market clearing conditions, (4) and (5), are satisfied;*
- *tax revenues are given by (6).*

Proof of Lemma 1. The first-order condition for the supply of labor is $\nu'(\ell) = w$ and for the supply of capital is $\phi'(k) = R$. The unit cost of producing task x with labor is

$$p^\ell(x) = \frac{w}{\psi^\ell(x)},$$

whereas the unit cost of producing task x with capital is

$$p^k(x) = \frac{R}{\psi^k(x)}$$

Because the allocation of tasks to factors is cost-minimizing and because $\psi^\ell(x)/\psi^k(x)$ is (strictly) increasing, there exists a threshold θ such that all tasks below the threshold are produced with capital and those above it will be produced with labor.

The demand for capital in the economy therefore comes from tasks $x \leq \theta$ and satisfies

$$\begin{aligned} k &= \int_0^\theta k(x)dx \\ &= \int_0^\theta \frac{y(x)}{\psi^k(x)}dx \\ &= \int_0^\theta \frac{y \cdot p^k(x)^{-\lambda}}{\psi^k(x)}dx \\ &= y \cdot R^{-\lambda} \cdot \int_0^\theta \psi^k(x)^{\lambda-1}dx, \end{aligned}$$

which can be rearranged as

$$R = \left(\frac{y}{k}\right)^{\frac{1}{\lambda}} \cdot \left(\int_0^\theta \psi^k(x)^{\lambda-1}dx\right)^{\frac{1}{\lambda}}. \tag{A.1}$$

Combining this equation with the first-order condition for the supply of capital, we obtain the capital-market clearing condition in (4).

Likewise, the demand for labor comes from tasks $x > \theta$ and is given by

$$\begin{aligned} \ell &= \int_\theta^1 \ell(x)dx \\ &= \int_\theta^1 \frac{y(x)}{\psi^\ell(x)}dx \\ &= \int_\theta^1 \frac{y \cdot p^\ell(x)^{-\lambda}}{\psi^\ell(x)}dx \\ &= y \cdot w^{-\lambda} \int_\theta^1 \psi^\ell(x)^{\lambda-1}dx. \end{aligned}$$

Therefore,

$$w = \left(\frac{y}{\ell}\right)^{\frac{1}{\lambda}} \cdot \left(\int_\theta^1 \psi^\ell(x)^{\lambda-1}dx\right)^{\frac{1}{\lambda}}. \tag{A.2}$$

Combining this equation with the first-order condition for the supply of labor, we obtain the labor-market clearing condition (5).

We next prove that aggregate output is given by $f(k, \ell; \theta)$. Since the final good is the numeraire, the ideal price condition is

$$1 = \int_0^\theta p^k(x)^{1-\lambda}dx + \int_\theta^1 p^\ell(x)^{1-\lambda}dx.$$

Substituting task prices in terms of factor prices net of taxes, this condition yields

$$1 = R^{1-\lambda} \cdot \int_0^\theta \psi^k(x)^{\lambda-1} dx + w^{1-\lambda} \cdot \int_\theta^1 \psi^\ell(x)^{\lambda-1} dx.$$

Replacing the expressions for R and w from equations (A.1) and (A.2), we obtain the ideal price condition in terms of aggregate output, capital, labor, the level of automation and the production parameters:

$$\begin{aligned} 1 = &\left(\frac{y}{k}\right)^{\frac{1-\lambda}{\lambda}} \cdot \left(\int_0^\theta \psi^k(x)^{\lambda-1} dx\right)^{\frac{1}{\lambda}} \\ &+ \left(\frac{y}{\ell}\right)^{\frac{1-\lambda}{\lambda}} \cdot \left(\int_\theta^1 \psi^\ell(x)^{\lambda-1} dx\right)^{\frac{1}{\lambda}}. \end{aligned}$$

Equation (2) follows by solving for y in the above equation.

We now turn to the determination of θ. Because task allocations are cost-minimizing, the thresholds task θ satisfies

$$\frac{w}{\psi^\ell(x)} = \frac{R}{\psi^k(x)} \Rightarrow \frac{w}{R} = \frac{\psi^\ell(\theta)}{\psi^k(\theta)}.$$

Using the fact that $R = f_k \cdot (1 - \tau^k)$ and $w = f_\ell \cdot (1 - \bar{\varrho}) \cdot (1 - \tau^\ell)$, we can rewrite this as:

$$\frac{f_\ell}{f_k} = \frac{\psi^\ell(\theta)}{\psi^k(\theta)}. \tag{A.3}$$

This equation has a unique solution $\theta^m(k, \ell)$. Uniqueness is a consequence of the fact that the right-hand side is continuous and increasing in θ (by assumption), and the left-hand side,

$$\frac{f_\ell}{f_k} = \left(\frac{k}{\ell} \frac{\int_\theta^1 \psi^\ell(x)^{\lambda-1} dx}{\int_0^\theta \psi^k(x)^{\lambda-1} dx}\right)^{\frac{1}{\lambda}},$$

is decreasing in θ. The solution always exists because the left-hand side goes from ∞ (at $\theta = 0$) to 0 (at $\theta = 1$).

We now show that $\theta^m(k, \ell)$ maximizes $f(k, \ell; \theta)$. An infinitesimal change in θ leads to a change in aggregate output of

$$f_\theta(k, \ell; \theta) = \frac{y}{1-\lambda} \left(\left(\frac{f_\ell}{\psi^\ell(\theta)}\right)^{1-\lambda} - \left(\frac{f_k}{\psi^k(\theta)}\right)^{1-\lambda} \right). \tag{A.4}$$

This expression follows by totally differentiating (2), which yields

$$f_\theta(k,\ell;\theta) = \frac{1}{1-\lambda}\psi^\ell(\theta)^{\lambda-1}\cdot y^{\frac{1}{\lambda}}\cdot \ell^{\frac{\lambda-1}{\lambda}}\cdot\left(\int_\theta^1 \psi^\ell(x)^{\lambda-1}dx\right)^{\frac{1-\lambda}{\lambda}}$$
$$-\frac{1}{1-\lambda}\psi^k(\theta)^{\lambda-1}\cdot y^{\frac{1}{\lambda}}\cdot k^{\frac{\lambda-1}{\lambda}}\cdot\left(\int_0^\theta \psi^k(x)^{\lambda-1}dx\right)^{\frac{1-\lambda}{\lambda}}.$$

Regrouping terms yields

$$f_\theta(k,\ell;\theta) = \frac{y}{1-\lambda}\left(\psi^\ell(\theta)^{\lambda-1}\cdot\left(\frac{y}{\ell}\cdot\int_\theta^1 \psi^\ell(x)^{\lambda-1}dx\right)^{\frac{1-\lambda}{\lambda}} - \psi^k(\theta)^{\lambda-1}\cdot\left(\frac{y}{k}\cdot\int_0^\theta \psi^k(x)^{\lambda-1}dx\right)^{\frac{1-\lambda}{\lambda}}\right).$$

Equation (A.4) follows after substituting in the formulas for f_k and f_ℓ in place of the terms in the inner parentheses.

Equation (A.4) further implies $f_\theta \geq 0$ to the left of $\theta^m(k,\ell)$, since in this region we have

$$\frac{f_\ell}{f_k} > \frac{\psi^\ell(\theta)}{\psi^k(\theta)}.$$

Moreover, $f_\theta < 0$ the right of $\theta^m(k,\ell)$, since in this region we have

$$\frac{f_\ell}{f_k} < \frac{\psi^\ell(\theta)}{\psi^k(\theta)}.$$

Thus, $f(k,\ell,\theta)$ is single-peaked with a unique maximum at $\theta^m(k,\ell)$.

Finally, we compute equilibrium tax revenues. Capital taxes, which raise revenue from tasks below θ, generate total revenue:

$$\text{Revenue capital taxes} = \int_0^\theta \tau^k\cdot R\cdot k(x)dx = \tau^k\cdot f_k\cdot k,$$

where we used the fact that $R = f_k$ (from equation (A.1)). Likewise, labor taxes raise revenue from tasks above θ and thus:

$$\text{Revenue labor taxes} = \int_0^\theta \tau^\ell\cdot w\cdot \ell(x)dx = \tau^\ell\cdot f_\ell\cdot \ell,$$

where we used the fact that $w = f_\ell$ (from equation (A.2)). ■

The next lemma is straightforward but will be used repeatedly in our proofs.

Lemma 2 *The production function $f(k,\ell;\theta^m(k,\ell))$ exhibits constant returns to scale and is concave in k and ℓ.*

Proof. We first show that $f(k,\ell;\theta^m(k,\ell))$ exhibits constant returns to scale. Because $f(\lambda k,\lambda\ell;\theta) = \lambda f(k,\ell;\theta)$ (which is immediate from (2)), it is sufficient to prove that $\theta^m(k,\ell)$ is homogeneous of degree zero. Equation (A.3) implies that $\theta^m(k,\ell)$ is the unique solution to

$$\left(\frac{k}{\ell}\frac{\int_\theta^1 \psi^\ell(x)^{\lambda-1}dx}{\int_0^\theta \psi^k(x)^{\lambda-1}dx}\right)^{\frac{1}{\lambda}} = \frac{\psi^\ell(\theta)}{\psi^k(\theta)},$$

which shows that $\theta^m(k,\ell)$ only depends on k/ℓ and is thus homogeneous of degree zero.

Since $f(k,\ell;\theta^m(k,\ell))$ exhibits constant returns to scale in k and ℓ, it is concave if and only if it is quasi-concave in k and ℓ. Note that $h(k,\ell) = f(k,\ell;\theta^m(k,\ell))$ solves the optimization problem:

$$\text{(A.5)} \qquad f(k,\ell;\theta^m(k,\ell)) = \max_{k(x),\ell(x)\geq 0}\left(\int_0^1 y(x)^{\frac{\lambda-1}{\lambda}}dx\right)^{\frac{\lambda}{\lambda-1}},$$

$$\text{subject to: } y(x) = \psi^k(x)k(x) + \psi^\ell(x)\ell(x)$$

$$\int_0^1 k(x)dx = k$$

$$\int_0^1 \ell(x)dx = \ell.$$

Suppose that $h(k_1,\ell_1) \geq b$ and $h(k_2,\ell_2) \geq b$, and denote by $\{k_1(x),\ell_1(x),y_1(x)\}$ and $\{k_2(x),\ell_2(x),y_2(x)\}$ the solution to (A.5) for $\{k_1,\ell_1\}$ and $\{k_2,\ell_2\}$, respectively. Consider the problem in (A.5) for $\{\alpha k_1 + (1-\alpha)k_2, \alpha\ell_1 + (1-\alpha)\ell_2\}$ for some $\alpha \in [0,1]$. The allocation $\{\alpha k_1(x) + (1-\alpha)k_2(x), \alpha\ell_1(x) + (1-\alpha)\ell_2(x), \alpha y_1(x) + (1-\alpha)y_2(x)\}$ satisfies all the constraint in (A.5). It follows that

$$h(\alpha k_1 + (1-\alpha)k_2, \alpha\ell_1 + (1-\alpha)\ell_2) \geq \left(\int_0^1 (\alpha y_1(x) + (1-\alpha)y_2(x))^{\frac{\lambda-1}{\lambda}}dx\right)^{\frac{\lambda}{\lambda-1}}.$$

Using the concavity of the constant elasticity of substitution function on the right-hand side of the above equation, we get

$$h(\alpha k_1 + (1-\alpha)k_2, \alpha\ell_1 + (1-\alpha)\ell_2)\alpha\left(\int_0^1 y_1(x)^{\frac{\lambda-1}{\lambda}}dx\right)^{\frac{\lambda}{\lambda-1}} + (1-\alpha)\left(\int_0^1 y_2(x)^{\frac{\lambda-1}{\lambda}}dx\right)^{\frac{\lambda}{\lambda-1}} \geq b.$$

It follows that $h(k,\ell) = f(k,\ell;\theta^m(k,\ell))$ is quasi-concave in k and ℓ and hence concave in k and ℓ, completing the proof. ■

Main Proofs

In this section of the Appendix, we provide the proofs of the main results stated in the text. Before presenting the proofs of the results in the text, we provide a derivation of the Implementability Condition (IC) in (7). Exploiting the fact that f has constant returns to scale, we can rewrite the government budget constraint as follows

$$\begin{aligned} g \leq & \tau^k \cdot f_k \cdot k + \tau^\ell \cdot f_\ell \cdot \ell \\ = & f(k,\ell;\theta) - (1-\tau^k) \cdot f_k \cdot k - (1-\tau^\ell) \cdot f_\ell \cdot \ell. \end{aligned}$$

Using the capital and labor-market clearing condition in equations (4) and (5), we can substitute out the terms $(1-\tau^k) \cdot f_k$ and $(1-\tau^\ell) \cdot f_\ell$, which gives

$$\begin{aligned} g \leq & f(k,\ell;\theta) - (1-\tau^k) \cdot f_k \cdot k - (1-\tau^\ell) \cdot f_\ell \cdot \ell \\ = & f(k,\ell;\theta) - \phi'(k) \cdot k - \frac{\nu'(\ell) \cdot \ell}{1-\varrho}, \end{aligned}$$

which is the Implementability Condition used in the main text.

We next present the proofs of our main results.

Proof of Proposition 1. We start by solving for the optimal allocation. The utility of the representative household is given by

$$\text{utility} := c - \nu(\ell) = f(k,\ell;\theta) - \phi(k) - \nu(\ell) - g.$$

The Ramsey problem can therefore be written as

$$\max_{k,\ell,\theta} f(k,\ell;\theta) - \phi(k) - \nu(\ell) \text{ subject to: } g \leq f(k,\ell;\theta) - \phi'(k) \cdot k - \frac{\nu'(\ell) \cdot \ell}{1-\varrho}.$$

Both the objective function and the constraint are increasing in θ. It follows that θ maximizes $f(k,\ell;\theta)$, and this implies that $\theta = \theta^m(k,\ell)$ as claimed in the proposition. In particular, we have $f_\theta(k,\ell;\theta^m(k,\ell)) = 0$.

With this choice, the problem becomes

$$\max_{k,\ell,\theta} f(k,\ell;\theta^m(k,\ell)) - \phi(k) - \nu(\ell) \text{ subject to: } g \leq f(k,\ell;\theta^m(k,\ell)) - \phi'(k) \cdot k - \frac{\nu'(\ell) \cdot \ell}{1-\varrho}.$$

We next prove that the objective function is concave and the constraints that is convex.

The concavity of the objective function follows from Lemma 2 and the fact that $\phi(k)$

and $\nu(\ell)$ are convex. The constraint $g \le f(k,\ell;\theta^m(k,\ell)) - \phi'(k)\cdot k - \frac{\nu'(\ell)\cdot\ell}{1-\varrho}$ defines a convex set since Lemma 2 implies that $f(k,\ell;\theta^m(k,\ell))$ is concave and $\phi'(k)\cdot k$ and $\frac{\nu'(\ell)\cdot\ell}{1-\varrho}$ are convex functions.

Thus, the optimal problem is equivalent to the maximization of a concave function over a convex set. This implies that for any $g > 0$, the optimum is unique and yields some utility $\mathcal{W}$. Figure A.3 illustrates this optimum. The figure plots the set of points that satisfies the IC constraintthe points within the iso-revenue curve for $g$and also identifies the set of points that yield higher utility than the optimal allocation, which are those inside this contour set of $\mathcal{W}$. The optimal allocation is given by the tangency point between the iso-revenue curve and the contour sets of $\mathcal{W}$.

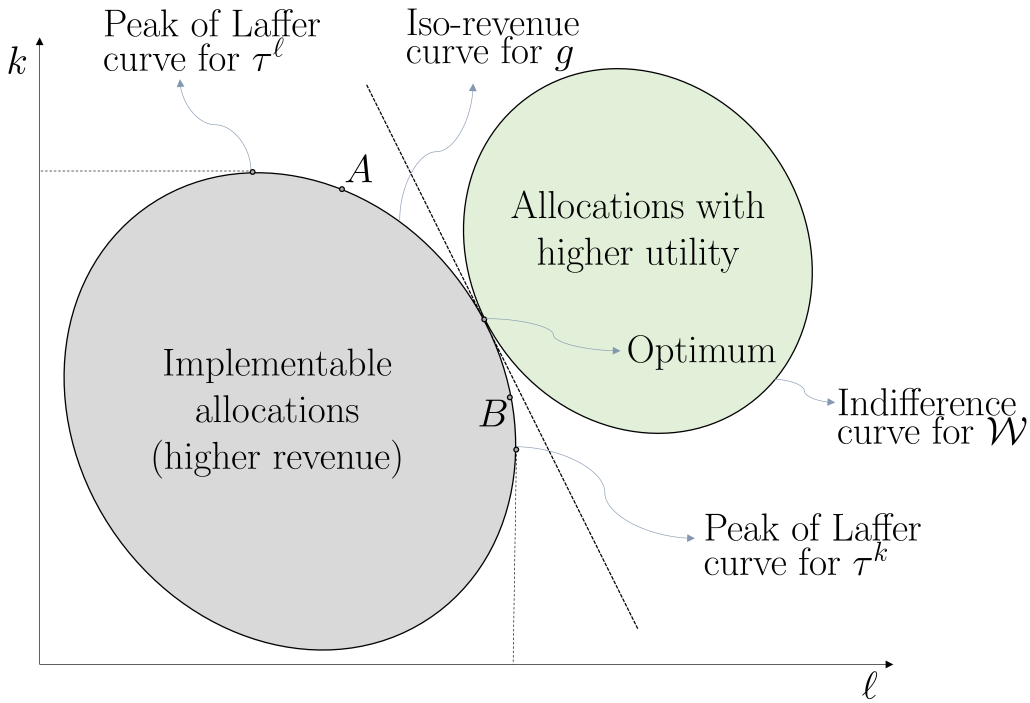

FIGURE A.3: Illustration of optimal policy problem.

At this point, the marginal utility per unit of revenue loss from an increase in k (denoted by $U^k(k,\ell)$) equals the marginal utility per unit of revenue loss from a increase in ℓ (denoted by $U^k(k,\ell)$), and both are equal to the multiplier μ, which denotes the marginal utility per unit of additional revenue. These marginal utilities can be computed as

$$U^k(k,\ell) := -\frac{\partial \text{utility}}{\partial k}\Bigg/\frac{\partial \text{revenue}}{\partial k} = \frac{f_k - \phi'(k)}{\phi''(k)\cdot k + \phi'(k) - f_k},$$

$$U^\ell(k,\ell) := -\frac{\partial \text{utility}}{\partial \ell}\Bigg/\frac{\partial \text{revenue}}{\partial \ell} = \frac{f_\ell - \nu'(\ell)}{\frac{\nu''(\ell)}{1-\varrho}\cdot\ell + \frac{\nu'(\ell)}{1-\varrho} - f_\ell}.$$

Therefore, the optimum allocation is given by the unique set of points along the iso-revenue curve for g for which

$$U^k(k,\ell) = U^\ell(k,\ell) = \mu.$$

We next prove that this unique optimal allocation can be implemented using the taxes in (8). Starting from $U^k(k,\ell) = \mu$, we obtain

$$U^k(k,\ell) = \frac{f_k - \phi'(k)}{\phi''(k)\cdot k + \phi'(k) - f_k} = \mu.$$

Dividing the numerator and denominator on the left-hand side by $\phi'(k)$ and using (4) to substitute out for f_k, yields

$$\frac{\frac{\tau^k}{1-\tau^k}}{\frac{1}{\varepsilon^k(k)} - \frac{\tau^k}{1-\tau^k}} = \mu,$$

which after rearrangement gives the formula for $\tau^k/(1-\tau^k)$ in (8).

Likewise, starting from $U^\ell(k,\ell) = \mu$, we obtain

$$U^\ell(k,\ell) = \frac{f_\ell - \nu'(\ell)}{\frac{\nu''(\ell)}{1-\varrho}\cdot \ell + \frac{\nu'(\ell)}{1-\varrho} - f_\ell} = \mu.$$

Dividing the numerator and denominator on the left-hand side by $\nu'(\ell)/(1-\varrho)$ and using (5) to substitute out for f_ℓ, we obtain

$$\frac{\frac{\tau^\ell}{1-\tau^\ell} + \varrho}{\frac{1}{\varepsilon^\ell(\ell)} - \frac{\tau^\ell}{1-\tau^\ell}} = \mu,$$

which after rearrangement gives the formula for $\tau^\ell/(1-\tau^\ell)$ in (8). ∎

Proof of Corollary 1. Obtained by substituting $\varepsilon^k(k) = \varepsilon^\ell(\ell)$ and $\varrho = 0$ in (8). ∎

Proof of Corollary 2. First, note that the function $U^k(k,\ell)$ is decreasing in k and increasing in ℓ (because $\phi'(k)\cdot k$ and $\phi(k)$ are convex, and therefore their derivatives $\phi'(k) + \phi''(k)\cdot k$ and $\phi'(k)$ are increasing in k, and, from Lemma 2, f_k is decreasing in k and is increasing in ℓ). Likewise, the function $U^\ell(k,\ell)$ is increasing in k and decreasing in ℓ (because $\nu'(\ell)\cdot\ell$ and $\nu(\ell)$ are convex and therefore their derivatives $\nu'(\ell)+\nu''(\ell)\cdot\ell$ and $\nu'(\ell)$ are increasing in ℓ, and, from Lemma 2, f_ℓ is decreasing in ℓ and is increasing in k).

Consider a suboptimal tax system (τ^k,τ^ℓ) implementing an allocation along the iso-revenue curve for g in Figure A.3. There are three possibilities for this allocation. This allocation is either in the segment between the optimum and the peak of the Laffer curve for τ^ℓ (point A in Figure A.3); or between the optimum and the peak of the Laffer curve for τ^k (point B in Figure A.3); or it is beyond the peak of the Laffer curve (meaning that k and ℓ are too low, and both taxes are too high and they can both be decreased to increase revenue). The corollary assumes that the tax system is not beyond the peak of the Laffer curve (this is without loss of any generality, since the planner would never wish to set such taxes).

At point A, capital is above the optimum and employment is below the optimum. Therefore,

$$U^\ell(k,\ell) > \mu^* > U^k(k,\ell),$$

where μ^* is the Lagrange multiplier at the optimum allocation. The inequality $U^\ell(k,\ell) > U^k(k,\ell)$ implies

$$\frac{f_\ell - \nu'(\ell)}{\frac{\nu''(\ell)\cdot\ell}{1-\varrho} + \frac{\nu'(\ell)}{1-\varrho} - f_\ell} > \frac{f_k - \phi'(k)}{\phi''(k)\cdot k + \phi'(k) - f_k}.$$

Dividing the numerator and the denominator on the left-hand side by $\nu'(\ell)/(1-\varrho)$, and the numerator and the denominator on the right-hand side by $\phi'(k)$, and using the definition of $\varepsilon^\ell(\ell)$ and $\varepsilon^k(k)$ yields (9).

Finally, we prove that τ^k and τ^ℓ satisfy $\tau^\ell > \tau^{\ell,r}$ and $\tau^{k,r} > \tau^k$. In particular, observe that the market-clearing condition for capital is

$$1 - \tau^k = \frac{\phi'(k)}{f_k}.$$

The numerator on the right-hand side increases with k, and the denominator decreases in k and increases in ℓ (this is due to the concavity of f by Lemma 2 and the fact that f exhibits constant returns to scale). Thus, the right-hand side of this equation increases as we move from the optimal allocation to the current allocation, which implies $\tau^{k,r} > \tau^k$. Likewise,

$$1 - \tau^\ell = \frac{\nu'(\ell)}{(1-\varrho)\cdot f_\ell}.$$

The numerator on the right-hand side increases with ℓ, and the denominator decreases in ℓ and increases in k (this is due to the concavity of f by Lemma 2 and the fact that f exhibits constant returns to scale). Therefore, the right-hand side of this equation decreases as we move from the optimal allocation to the current one, which implies $\tau^{\ell,r} < \tau^\ell$.

the proof that, at point B, the opposite of (9) holds is analogous and implies that in this region $\tau^{\ell,r} > \tau^\ell$ and $\tau^{k,r} < \tau^k$.

It follows that (9) is a necessary and sufficient condition for the tax system to be biased against labor and in favor of capital (and to lead to an equilibrium with employment below the optimum and the capital stock above the optimum). ■

Proof of Proposition 2. We can write the equilibrium quantities of capital and labor as $k(\theta)$ and $\ell(\theta)$, which are implicitly determined by (4) and (5).

Differentiating (4) and (5), we obtain that after an infinitesimal change in θ, the change in employment and capital are given by the solution to the system of equations:

$$\left(\frac{\nu''(\ell)}{(1-\varrho)\cdot(1-\tau^{\ell})} - f_{\ell\ell}\right)\cdot \ell_{\theta} - f_{\ell k}\cdot k_{\theta} = f_{\ell\theta} \qquad -f_{k\ell}\cdot \ell_{\theta} + \left(\frac{\phi''(k)}{1-\tau^{k}} - f_{kk}\right)\cdot k_{\theta} = f_{k\theta},$$

which has a unique solution given by

$$\ell_{\theta} = \frac{f_{\ell\theta}\cdot\left(\frac{\phi''(k)}{1-\tau^{k}} - f_{kk}\right) + f_{k\theta}\cdot f_{\ell k}}{\left(\frac{\nu''(\ell)}{(1-\varrho)\cdot(1-\tau^{\ell})} - f_{\ell\ell}\right)\cdot\left(\frac{\phi''(k)}{1-\tau^{k}} - f_{kk}\right) - f_{k\ell}\cdot f_{\ell k}}$$

$$k_{\theta} = \frac{f_{k\theta}\cdot\left(\frac{\nu''(\ell)}{(1-\varrho)\cdot(1-\tau^{\ell})} - f_{\ell\ell}\right) + f_{\ell\theta}\cdot f_{k\ell}}{\left(\frac{\nu''(\ell)}{(1-\varrho)\cdot(1-\tau^{\ell})} - f_{\ell\ell}\right)\cdot\left(\frac{\phi''(k)}{1-\tau^{k}} - f_{kk}\right) - f_{k\ell}\cdot f_{\ell k}}$$

Note that $f_{\theta}(k,\ell;\theta)$ has constant returns to scale in k and ℓ. Moreover, at $\theta = \theta^{m}(k,\ell)$, we have $f_{\theta} = 0$. The Euler theorem implies that $kf_{\theta k} + \ell f_{\theta\ell} = 0$. But this implies $f_{\theta k} > 0 > f_{\theta\ell}$. A second application of Euler theorem yields $kf_{kk} + \ell f_{k\ell} = 0$; and a third application gives $kf_{\ell k} + \ell f_{\ell\ell} = 0$. It follows that, at $\theta = \theta^{m}(k,\ell)$, the following identities hold

$$f_{\ell\theta}\cdot f_{kk} = f_{k\theta}\cdot f_{\ell k} \qquad f_{k\theta}\cdot f_{\ell\ell} = f_{\ell\theta}\cdot f_{k\ell} \qquad f_{\ell\ell}\cdot f_{kk} = f_{k\ell}\cdot f_{\ell k}.$$

Using these identities, we can simplify the formulas for ℓ_{θ} and k_{θ} above as

$$\ell_{\theta} = \frac{f_{\ell\theta}\cdot\frac{\phi''(k)}{1-\tau^{k}}}{\Lambda} < 0 \qquad k_{\theta} = \frac{f_{k\theta}\cdot\frac{\nu''(\ell)}{(1-\varrho)\cdot(1-\tau^{\ell})}}{\Lambda} > 0,$$

where $\Lambda = \frac{\nu''(\ell)}{(1-\varrho)\cdot(1-\tau^{\ell})}\cdot\frac{\phi''(k)}{1-\tau^{k}} - f_{kk}\cdot\frac{\nu''(\ell)}{(1-\varrho)\cdot(1-\tau^{\ell})} - f_{\ell\ell}\cdot\frac{\phi''(k)}{1-\tau^{k}} > 0$. This establishes the main result of the proposition: reducing θ below $\theta^{m}(k,\ell)$ will always result in an increase in employment and a reduction in capital.

To complete the proof of the proposition,we next explore the first-order implications of these changes for welfare and output. Welfare is given by

$$\mathcal{W} = f(k,\ell;\theta) - \nu(\ell) - \phi(k) + \mu^{*}\cdot\left(f(k,\ell;\theta^{m}(k,\ell)) - \phi'(k)\cdot k - \frac{\nu'(\ell)\cdot\ell}{1-\varrho} - g\right),$$

where μ^{*} denotes the Lagrange multiplier at the optimum allocation.

Following an infinitesimal change in θ, welfare changes by

$$\frac{d\mathcal{W}}{d\theta} = \mathcal{W}_\ell \cdot \ell_\theta + \mathcal{W}_k \cdot k_\theta + (1+\mu^*) \cdot f_\theta,$$

where $\mathcal{W}_\ell$ and $\mathcal{W}_k$ denote the changes in welfare arising from improvements in allocative efficiency.

Suppose that the current tax system satisfies (9). Corollary 2 implies that $U^\ell(k,\ell) > \mu^* > U^k(k,\ell)$—that is, employment is too low and capital too high. It follows that

$$\begin{aligned}\mathcal{W}_\ell =& f_\ell - \nu'^* \cdot \left(\frac{\nu''(\ell)}{1-\varrho} \cdot \ell + \frac{\nu'(\ell)}{1-\varrho} - f_\ell\right) > 0 \Leftrightarrow U^\ell(k,\ell) > \mu^* \\ \mathcal{W}_k =& f_k - \phi'^* \cdot (\phi''(k) \cdot k + \phi'(k) - f_k) < 0 \Leftrightarrow U^\ell(k,\ell) < \mu^*,\end{aligned}$$

so that welfare increases as employment increases and capital is reduced.

Moreover, starting from $\theta = \theta^m(k,\ell)$, we have $f_\theta = 0$, $\ell_\theta > 0$ and $k_\theta > 0$. Therefore,

$$\frac{d\mathcal{W}}{d\theta} < 0,$$

and welfare increases following an infinitesimal reduction in θ.

We now turn to the implications of a reduction in θ for output and for revenue. The change in output at $\theta^m(k,\ell)$ is

$$\frac{dy}{d\theta} = f_\ell \cdot \ell_\theta + f_k \cdot k_\theta,$$

which can be written as

$$\frac{dy}{d\theta} = -\frac{f_\ell \cdot f_k \cdot f_{k\theta}}{\ell \cdot \Lambda} \left(\frac{\phi''(k) \cdot k}{\phi'(k)} - \frac{\nu''(\ell) \cdot \ell}{\nu'(\ell)}\right).$$

Thus, an infinitesimal reduction in θ will also expand output if $\varepsilon^\ell(\ell) > \varepsilon^k(k)$, as claimed in the Proposition.

Finally, the change in revenue near $\theta^m(k,\ell)$ is

$$\frac{d\text{revenue}}{d\theta} = \left(f_\ell - \frac{\nu'(\ell)}{1-\varrho} - \frac{\nu''(\ell) \cdot \ell}{1-\varrho}\right) \cdot \ell_\theta + (f_k - \phi'(k) - \phi''(k) \cdot k) \cdot k_\theta,$$

which can be written as

$$\frac{d\text{revenue}}{d\theta} = \frac{\nu'(\ell) \cdot \phi'(k) \cdot f_{k\theta}}{\ell \cdot (1-\varrho) \cdot \Lambda} \cdot \frac{\tau^k \cdot (1+\varepsilon^k) - \tau^\ell \cdot (1+\varepsilon^\ell)}{\varepsilon^k \cdot \varepsilon^\ell \cdot (1-\tau^k) \cdot (1-\tau^\ell)}.$$

Thus, an infinitesimal reduction in θ will also expand revenue if $\tau^\ell \cdot (1+\varepsilon^\ell(\ell)) > \tau^k \cdot (1+\varepsilon^k(k))$, as claimed. ■

Proof of Proposition 3. The constrained Ramsey problem can be written as

$$\max_{k,\ell,\theta} f(k,\ell;\theta) \text{ subject to: } g \leq f(k,\ell;\theta) - \phi'(k)\cdot k - \frac{\nu'(\ell)\cdot \ell}{1-\varrho}$$
$$\nu'(\ell) \leq (1-\bar{\tau}^{\ell})\cdot(1-\varrho)\cdot f_{\ell}$$

Let $\mu > 0$ and $\gamma^{\ell} \geq 0$ denote the multipliers on the IC constraint and the constraint on labor taxes, respectively. We assume throughout that the constraint on labor taxes binds, so that $\gamma^{\ell} > 0$.

The first-order condition with respect to capital is given by

$$f_k - \phi'(k) - \mu\cdot(\phi''(k)\cdot k + \phi'(k) - f_k) + \gamma^{\ell}\cdot(1-\bar{\tau}^{\ell})\cdot(1-\varrho)\cdot f_{\ell k}.$$

Dividing by $\phi'(k)$, using the capital market-clearing condition (4) to substitute for f_k, and rearranging yields (11).

Note next that the choice of θ^c maximizes the Lagrangean of the constrained Ramsey problem. Thus, we have

$$\theta^c = \arg\max_{\theta\in[0,1]}(1+\mu)\cdot f(k,\ell;\theta) + \gamma^{\ell}\cdot(1-\bar{\tau}^{\ell})\cdot(1-\varrho)\cdot f_{\ell}(k,\ell;\theta).$$

Denote by $g(\theta)$ the right-hand of this equation. We now show that $g(\theta)$ is strictly decreasing for $\theta \geq \theta^m(k,\ell)$. To prove this, note that

$$f_{\ell\theta}(k,\ell;\theta) = \frac{1}{\lambda} f_{\theta}(k,\ell;\theta)\frac{1}{\ell}\cdot\left(\frac{y}{\ell}\right)^{\frac{1}{\lambda}-1}\cdot\left(\int_{\theta}^{1}\psi^{\ell}(x)^{\lambda-1}dx\right)^{\frac{1}{\lambda}} - \frac{1}{\lambda}\psi^{\ell}(\theta)^{\lambda-1}\cdot\left(\frac{y}{\ell}\right)^{\frac{1}{\lambda}-1}\cdot\left(\int_{\theta}^{1}\psi^{\ell}(x)^{\lambda-1}dx\right)^{\frac{1}{\lambda}},$$

which is negative for $\theta \geq \theta^m(k,\ell)$. Moreover, $f_{\theta}(k,\ell;\theta)$ is zero at $\theta^m(k,\ell)$ and negative for all $\theta > \theta^m(k,\ell)$. Therefore, $g(\theta)$ is strictly decreasing for $\theta \geq \theta^m(k,\ell)$ (note that if we did not have $\gamma^{\ell} > 0$, $g(\theta)$ could not be strictly decreasing at $\theta^m(k,\ell)$).

Finally, because $g(\theta)$ is strictly decreasing for $\theta \geq \theta^m(k,\ell)$, we must have $\theta^c < \theta^m(k,\ell)$ as claimed. ■

Proof of Proposition 4. See next section. ■

Additional Results

The next proposition provides three alternative ways of implementing the desired level of automation via taxes and subsidies, one of which coincides with the scheme presented in

Proposition 4 in the text.

PROPOSITION A.1 ***(Implementation of a reduction in θ via task-specific taxes and subsidies)*** *Consider any allocation $\{k,\ell,\theta\}$ that satisfies the implementability condition, and where $\theta \leq \theta^m(k,\ell)$. Let τ^k and τ^ℓ be given by*

$$1-\tau^k = \frac{\phi'(k)}{f_k} \qquad\qquad 1-\tau^\ell = \frac{\nu'(\ell)}{(1-\varrho)\cdot f_\ell}.$$

Moreover, define

$$\tau^A = 1 - \frac{f_k}{f_\ell}\cdot\frac{\psi^\ell(\theta)}{\psi^k(\theta)}.$$

The allocation $\{k,\ell,\theta\}$ can be implemented in any of the following ways:

- *A uniform tax τ^ℓ on labor and the following tax schedule on capital:*

$$\tau^k(x) = \begin{cases} \tau^k & \text{for } x \leq \theta \\ \tau^k + \tau^A & \text{for } x > \theta \end{cases}$$

- *A uniform tax τ^ℓ on labor, a uniform tax $\tau^k + \tau^A$ on capital, and a subsidy to tasks below θ at the same rate τ^A.*

- *A uniform tax $\tau^\ell - \tau^A$ on labor, a uniform tax τ^k on capital, and a tax on tasks above θ at the same rate τ^A.*

PROOF. TO BE COMPLETED. ■

The next proposition characterizes optimal capital and labor taxes when the planner cannot directly or indirectly influence automation decisions.

PROPOSITION A.2 ***(Indirect taxation of automation via uniform taxes on capital)*** *Consider the constrained Ramsey problem of maximizing (7) subject to the additional constraint $\tau^\ell \geq \bar{\tau}^\ell$, and suppose that in the solution to this problem (10) binds. In addition, suppose that the planner cannot distort the level of automation and must set $\theta = \theta^m(k,\ell)$. Then the constrained optimal taxes and allocation are a labor tax of $\tau^{\ell,c} = \bar{\tau}^\ell$ and a tax/subsidy on capital that satisfies*

$$\frac{\tau^{k,r}}{1-\tau^{k,r}} = \frac{\mu}{1+\mu}\cdot\frac{1}{\varepsilon^k(k)} - \frac{\gamma}{1+\mu}\cdot(1-\bar{\tau}^\ell)\cdot(1-\varrho)\cdot\frac{f_{\ell k}}{\phi'}$$
$$- \frac{\gamma^\ell}{1+\mu}\cdot(1-\bar{\tau}^\ell)\cdot(1-\varrho)\cdot\frac{f_{\ell\theta}\cdot\theta^m_k(k,\ell)}{\phi'},$$

where $f_{\ell\theta} \cdot \theta^m_k(k,\ell) < 0$, and the derivatives of f are evaluated at $k, \ell, \theta^m(k,\ell)$.

PROOF. TO BE COMPLETED. ■

The next proposition presents the analogue to Proposition 3, where there is an upper bound on capital taxes (rather than a lower bound on labor taxes).

PROPOSITION A.3 ***(Excessive automation when capital taxes are constrained)*** *Consider the constrained Ramsey problem of maximizing (7) subject to the additional constraint $\tau^k \leq \bar{\tau}^k$, so that*

$$\phi'(k) \geq (1 - \bar{\tau}^k) \cdot f_k$$

Suppose that in the solution to this problem, the above constraint binds and has multiplier $\gamma^k > 0$. Then the constrained optimal taxes and allocation are:

- *a capital tax of $\tau^{k,c} = \bar{\tau}^k$ and a tax/subsidy on labor $\tau^{\ell,c}$ such that*

$$\frac{\tau^{\ell,c}}{1 - \tau^{\ell,c}} = \frac{\mu}{1+\mu} \cdot \frac{1}{\varepsilon^\ell(\ell)} + \frac{\gamma^k}{1+\mu} \cdot (1 - \bar{\tau}^k) \cdot \frac{f_{k\ell}}{\nu'},$$

- *a level of automation $\theta^c < \theta^m(k,\ell)$.*

Moreover, the level of automation θ^c can be implemented through an extra subsidy to labor and a tax of the same magnitude on the output of tasks above θ^c (so that capital taxes still remain no greater than $\bar{\tau}^k$).

PROOF. TO BE COMPLETED. ■

Proofs of Extension Propositions in Section 5

TO BE COMPLETED.

A.3 Dynamic Model

This section presents a dynamic version of our model and derives two main results. The first one shows that, in the presence of a labor market wedge, if long-run capital taxes converge to zero, labor should be subsidized in order to undo the wedge. The second one shows that if there is an upper bound to the government budget (for example, for political economy reasons), which implies that the government cannot accumulate a very large wealth, then both capital and labor taxes converge to finite values and these values depend on the supply elasticities of these factors as in Proposition 1 in the text.

As in the text, we work with a representative agent economy. Preferences over sequences of consumption and work $\{(c_0, \ell_0), (c_1, \ell_1), \ldots\}$ at all points in time are given by

$$V_t = \mathcal{V}(u(c_t, \ell_t), u(c_{t+1}, \ell_{t+1}), \ldots),$$

where V_t is defined recursively as

$$V_t = \mathcal{W}(u(c_t, \ell_t), V_{t+1}). \tag{A.6}$$

The aggregator $\mathcal{W}$ satisfies the following properties

(W1) $\mathcal{W}$ is a continuous and increasing function from $\mathbb{R}^2$ to $\mathbb{R}$.

(W2) Its partial derivatives satisfies $\mathcal{W}_V \in (0, 1)$.

(W3) The resulting utility function $\mathcal{V}$ is concave over its domain.

The utility $u(c, \ell)$ is assumed normal in consumption and leisure (minus labor):

$$\frac{u_{cc}}{u_c} - \frac{u_{\ell c}}{u_\ell} \leq 0 \qquad\qquad \frac{u_{c\ell}}{u_c} - \frac{u_{\ell\ell}}{u_\ell} \leq 0.$$

Note that this is satisfied when using a quasi-linear utility preference as in the main text.

All of the derivations in this section follow Straub & Werning (2020) closely. As they do, we denote the derivative of X with respect to z at time t by X_{zt}. Also, it will be useful to define $\beta_t = \prod_{s=0}^{t-1} \mathcal{W}_{Vs}$. In addition, suppose a constant path of consumption and labor yields flow utility u and is valued at V. We can define the function $\bar{\beta}(V) = \mathcal{W}_V(u, V) \in (0, 1)$, where u satisfies $V = \mathcal{W}(u, V)$. When preferences are time separable, we have $V = u + \beta \cdot V$ and $\bar{\beta}(V) = \beta$. However, when preferences are not time separable, we will have $\bar{\beta}'(V) \neq 0$.

Starting from a given $k_0 > 0$, and given effective taxes on capital and labor τ_t^k and τ_t^ℓ, a competitive equilibrium is given by a sequence of consumption, labor, capital, and automation levels, $\{(c_0, \ell_0, k_0, \theta_0), (c_1, \ell_1, k_1, \theta_1), \ldots\}$, such that:

- production is given by $y_t = f(k_t, \ell_t; \theta_t)$, where $\theta_t = \theta^m(k_t, \ell_t)$;
- the Euler equation holds

$$\frac{\mathcal{V}_{ct-1}}{\mathcal{V}_{ct}} = 1 + (f_{kt} - \delta) \cdot (1 - \tau_t^k); \tag{A.7}$$

- the labor market clears

$$-\frac{u_{\ell t}}{u_{ct}} = f_{\ell t} \cdot (1 - \varrho) \cdot (1 - \tau_t^\ell); \tag{A.8}$$

- and the resource constraint holds

$$c_t + k_{t+1} + g \leq f(k_t, \ell_t; \theta_t) + (1 - \delta) k_t. \tag{A.9}$$

Optimal policy maximizes V_0 subject to the recursion (A.6), the Euler equation (A.7), the labor-market clearing condition (A.8), the resource constraint (A.9) and a government budget restriction. We first study an intertemporal budget restriction of the form

$$0 \leq \sum_{t=0}^{\infty} \mathcal{V}_{ct} \cdot (\tau_t^k \cdot f_{kt} \cdot k_t + \tau_t^\ell \cdot f_{\ell t} \cdot \ell_t), \tag{A.10}$$

where the assumption here is that government can issue debt or accumulate assets that yield a return equal to $\mathcal{V}_{ct-1}/\mathcal{V}_{ct}$, which is the gross rate of return required by the representative household. We will also study a different version of this problem where the government must keep a balanced budget.

Following the same steps as in Straub & Werning (2020), it follows that the Ramsey problem boils down to choosing a sequence of consumption, labor, capital, and automation θ, $\{(c_0, \ell_0, k_0, \theta_0), (c_1, \ell_1, k_1, \theta_1), \ldots\}$ that maximizes V_0 subject to the recursion (A.6), the resource constraint (A.9), and an *Implementability Constraint* (IC) that ensures that the taxes needed to implement that allocation are sufficient to cover the government expenditure:

$$\mathcal{V}_{c0} \cdot (R_0 \cdot k_0 + b_0) \leq \sum_{t=0}^{\infty} \mathcal{V}_{ct} \cdot c_t + \mathcal{V}_{\ell t} \cdot \frac{\ell_t}{1 - \varrho}. \tag{A.11}$$

Here, b_0 denotes the initial government debt including interest payments (or assets, if this were negative), and $R_0 = 1+(f_{k0}-\delta)\cdot(1-\tau_0^k)$ is the gross return on those assets. As is common in these problems, we assume that τ_t^k is bounded from above, so that the government cannot expropriate the capital stock at time 0 to satisfy the IC, and we focus on a situation where this constraint does not bind in the long run.

Our first proposition shows that, as in our static model, when optimal (unconstrained) taxes are in place, the planner will not distort automation decisions.

PROPOSITION A.4 *Suppose taxes are unconstrained. The solution to the dynamic Ramsey problem always involves setting $\theta_t = \theta^m(k_t, \ell_t)$.*

PROOF. θ_t only shows up in the term $f(k_t, \ell_t; \theta_t)$ in resource constraint (A.9). It follows that the optimal choice of θ maximizes $f(k_t, \ell_t; \theta_t)$ and coincides with $\theta^m(k_t, \ell_t)$. ■

Our second proposition is a generalization of Proposition 6 in Straub & Werning (2020) to the case with labor market imperfections.

PROPOSITION A.5 *Suppose that the Ramsey problem yields a solution where the allocation converges to an interior steady state where private wealth is non-zero. If $\bar{\beta}'(V) \neq 0$, in the long run optimal policy involves a zero tax on capital and a subsidy to labor that corrects for the labor market distortion introduced by ϱ.*

PROOF. Exploiting the recursive formulation of preferences, we can write the Ramsey problem as maximizing V_0 subject to $V_t = \mathcal{W}(u(c_t, \ell_t), V_{t+1})$, (A.9) and (A.11), which can be rewritten as

$$\mathcal{W}_{u0}u_{c0} \cdot (R_0 \cdot k_0 + b_0) \leq \sum_{t=0}^{\infty} \mathcal{W}_{ut}u_{ct} \cdot c_t + \mathcal{W}_{ut}u_{\ell t} \cdot \frac{\ell_t}{1-\varrho}. \tag{A.12}$$

Using the same notation as in Straub & Werning (2020), define

$$\begin{aligned} A_{t+1} =& \frac{1}{\beta_{t+1}} \frac{\partial}{\partial V_{t+1}} \sum_{s=0}^{\infty} \beta_s \mathcal{W}_{us} \cdot \left(u_{cs}c_s + u_{\ell s}\frac{1}{1-\varrho} \right) \\ B_t =& \frac{1}{\beta_t} \sum_{s=0}^{\infty} \frac{\partial(\beta_s \mathcal{W}_{us})}{\partial u_t} \cdot \left(u_{cs}c_s + u_{\ell s}\frac{1}{1-\varrho} \right). \end{aligned}$$

Because these objects depend only on the allocation, they asymptotically converge to A and B. The same holds for all the derivatives of components of the utility function or the production function with respect to changes in the allocation.

Moreover, as shown in Straub & Werning (2020), A satisfies

$$A = \frac{\bar{\beta}'(V)}{\bar{\beta}(V)} \cdot W_u u_c \cdot (1 + (f_k - \delta) \cdot (1 - \tau^c)) \cdot a,$$

where $a \neq 0$ (by assumption) is the wealth owned by the representative agent. It follows that, when $\bar{\beta}'(V) \neq 0$, $A \neq 0$.

Denote by $\beta_t \cdot \varsigma_t$ the multiplier on $V_t = \mathcal{W}(u(c_t, \ell_t), V_{t+1})$; by $\beta_t \lambda_t$ the multiplier on the resource constraint (A.9); and μ the multiplier on the Implementability Constraint, IC, (A.12). The first-order conditions for the Ramsey problem then converge to:

$$\begin{aligned} -\varsigma_t + \varsigma_{t+1} + \mu A =& 0 \\ -\varsigma_t W_u u_c + \mu W_u \cdot \left(u_c + u_{cc} \cdot c + u_{\ell c} \cdot \frac{\ell}{1-\varrho} \right) + \mu B u_c =& \lambda_t \\ \varsigma_t W_u u_\ell - \mu W_u \cdot \left(u_{c\ell} \cdot c + u_\ell \cdot \frac{1}{1-\varrho} + u_{\ell\ell} \cdot \frac{\ell}{1-\varrho} \right) - \mu B u_\ell =& \lambda_t f_\ell \\ -\lambda_t + \lambda_{t+1} W_V (1 + f_k - \delta) =& 0 \end{aligned}$$

Subtracting the second equation at time $t+1$ from the same equation at time t yields

$$W_u u_c \cdot (-\varsigma_t + \varsigma_{t+1}) = \lambda_t - \lambda_{t+1}.$$

Plugging $-\varsigma_t + \varsigma_{t+1}$ from the first equation, we thus obtain

$$\lambda_t - \lambda_{t+1} = -W_u u_c \mu A. \tag{A.13}$$

Likewise, eliminating ς_t from the first-order conditions for consumption and capital (the second and third first-order conditions above), we obtain

$$\lambda_t \left(f_\ell \cdot u_c + u_\ell \right) = \mu W_u u_c u_\ell \cdot \left(-\frac{\varrho}{1-\varrho} + \left(\frac{u_{cc}}{u_c} - \frac{u_{c\ell}}{u_\ell} \right) \cdot c + \left(\frac{u_{\ell c}}{u_c} - \frac{u_{\ell\ell}}{u_\ell} \right) \cdot \frac{\ell}{1-\varrho} \right). \tag{A.14}$$

The normality of consumption and leisure implies that the term in brackets is strictly negative.

If $\mu = 0$, equation (A.13) implies that $\lambda_t = \lambda_{t+1}$. The first order condition for capital (the fourth equation of the block) then gives

$$1 + f_k - \delta = \frac{1}{W_V} = \frac{1}{\bar{\beta}(V)},$$

which is equivalent to having zero taxes on capital (note that $\mathcal{V}_{ct-1}/\mathcal{V}_{ct} \to 1/W_V$). Likewise, equation (A.14) yields $f_\ell \cdot u_c + u_\ell = 0$, which implies that the labor tax is a subsidy that fully offsets the distortion introduced by ϱ. Thus, if $\mu = 0$, taxes are as claimed in the proposition.

Now suppose that $\mu \neq 0$. Equation (A.13) implies that λ_t diverges to $-\infty$ or ∞ (recall that

$\mu A \neq 0$). However, (A.14) then requires $f_\ell \cdot u_c + u_\ell$ to converge to zero, implies that, rather than a labor tax, labor should receive a subsidy that fully offsets the distortion introduced by ϱ. Likewise, the first order condition for capital (the fourth equation of the block) implies that

$$1 + f_k - \delta = \frac{1}{W_V} = \frac{\lambda_t}{\lambda_{t+1}} \frac{1}{\bar{\beta}(V)} \to \frac{1}{\bar{\beta}(V)},$$

since λ_t is an arithmetic series. This confirms that the long-run tax on capital is zero. ■

Intuitively, this proposition implies that the government should tax capital and labor heavily along the transition, and then manage to converge to the first-best allocation, fully undoing labor market frictions by using a subsidy to capital. The government must therefore accumulate vast amounts of assets to finance these labor subsidies and its regular expenditure perpetually.

While this is conceptually interesting, it is not realistic. For example, various political economy considerations would make it infeasible for the government to have a huge surplus. To introduce this constraint in the simplest possible way, we assume that the government must have a balanced budget every period, so that its budget constraint now becomes

$$g \leq \tau_t^k \cdot f_{kt} \cdot k_t + \tau_t^\ell \cdot f_{\ell t} \cdot \ell_t.$$

One can also think of the government as being constrained to holding no more than certain level of assets and g as the expenditure that cannot be covered by interest payments on those assets.

To obtain expressions that are comparable to our static model, we now work with the quasi-linear case $u(c, \ell) = c - \nu(\ell)$.

With this series of budget constraints, the Ramsey problem is now to maximize V_0 subject to the recursion in (A.6), the resource constraint (A.9), and the series of IC constraints

$$\text{(A.15)} \qquad g \leq f(k_t, \ell_t; \theta_t) + (1-\delta)k_t - \frac{1}{\mathcal{W}_{Vt-1}} \frac{W_{ut-1}}{W_{ut}} \cdot k_t - \nu'(\ell_t) \cdot \frac{\ell_t}{1-\varrho}.$$

Note that this IC is very similar to that in our static model, but with the marginal rate of substitution $\frac{1}{\mathcal{W}_{Vt-1}} \frac{W_{ut-1}}{W_{ut}}$ taking the role of $\phi'(k)$. Note in particular that, if the allocation converges, the IC becomes

$$g \leq f(k, \ell; \theta) + (1-\delta)k - \frac{1}{\bar{\beta}'(V)} \cdot k - \nu'(\ell) \cdot \frac{\ell}{1-\varrho},$$

and $1/\bar{\beta}'(V)$ plays the role of $\phi'(k)$.

Proposition A.6 *Consider the Ramsey problem of maximizing V_0 subject to the recursion in (A.6), the resource constraint (A.9), and the sequence of Implementability Constraints in (A.15). Suppose this problem yields a solution where the allocation converges to an interior steady state. If $\bar{\beta}'(V) \neq 0$, optimal policy involves non-zero taxes to capital and labor and no distortions to the automation level.*

Proof. To be completed. ■

A.4 Computation of Effective Tax Rates

Summary Table A.8 presents the sources and main computations required to obtain our measure of net operating surplus. The following sections describe the procedure we followed to compute the average taxes of interest, and the sources for our depreciation, investment price, and interest rate series.

Average Business Tax Rate on C-Corporations, $\tau^{\mathbf{c}}$

We first determine the average tax rates imposed on firms' profits *net of depreciation allowances*. The BEA produces series for capital consumption allowances for corporate and non-corporate taxpayers. We recover these series from FRED.[43] The national accounts classify as "corporate" all taxpayers that are subject to filing a form of the IRS series 1120, as reported in the NIPA Handbook. In particular, both C- and S-corporations are considered corporate. Notably, S-corporations are exempt from federal corporate income taxation, but this favorable treatment does not extend to all state and local business taxes.[44] In keeping with the foregoing discussion, we compute the tax base for state and local corporate taxes $\tau^{c,\mathrm{SL}}$ as the *net* operating surplus of C-corporations, $\mathrm{NOSCORP}^{\mathrm{IRS}}$, defined as the difference between the gross operating surplus of corporations. We calculate this measure as the sum of net operating surplus of corporations (line 8 of the BEA NIPA Table 1.14) and the consumption of fixed capital of corporations (line 12 of the BEA NIPA Table 1.14) minus the capital consumption allowances for corporations. We cannot directly use the consumption of fixed capital reported in the NIPA tables because they estimate the economic depreciation of the capital stock, while we are interested in recovering a measure of the *fiscal* depreciation of capital stocks. For this reason, we need to add back the NIPA consumption of fixed capital and then subtract the relevant allowances. The state and local tax revenues corresponding to the corporate tax base are given by the tax revenues from corporations at the state and local level (line 5 of BEA NIPA Table 3.3), $\mathrm{CT}^{\mathrm{SL}}$. We can thus estimate the capital tax faced by the corporate sector as

$$\tau_t^{c,\mathrm{SL}} = \frac{\mathrm{CT}_t^{\mathrm{SL}}}{\mathrm{NOSCORP}_t^{\mathrm{IRS}}}.$$

[43]The corresponding codes are A677RC1A027NBEA and A1700C0A144NBEA.

[44]For example, New York City, New Hampshire, California, Texas, and Tennessee do not recognize S-corporations for tax purposes. Other states have special rules on S-corporation election which do not necessarily match the federal criteria.

As mentioned above, the BEA also considers non-C-corporations as part of the corporate sector. However, only C-corporations are subject to federal taxes at the entity level, and the relevant tax base for federal corporate income taxes, $\tau^{c,\mathrm{SL}}$ is given by the net operating surplus of corporation that can be attributed to C-corporations, $\mathrm{NOSCORP}_t^{\mathrm{C,IRS}}$. Since NIPA tables do not provide a breakdown of corporate income by legal form of organization, we obtain the net income of corporations from the IRS SOI Tax Stats-Integrated Business data (IRS IBD), and compute share of C-corporations' net income in total corporate net income reported in IRS IBD Table 1,[45] which provides our estimate of the net operating surplus of C-corporations, $\mathrm{NOSCORP}_t^{\mathrm{C,IRS}}$. The federal revenues corresponding to this corporate tax base are given by the tax revenues from corporations at the federal level (line 5 of BEA NIPA Table 3.2), $\mathrm{CT}^{\mathrm{Fed}}$. Accordingly, the federal tax rate on capital income from C-corporations can be estimated as

$$\tau_t^{c,\mathrm{Fed}} = \frac{\mathrm{CT}_t^{\mathrm{Fed}}}{\mathrm{NOSCORP}_t^{\mathrm{C,IRS}}}.$$

Combining the federal, stat and local taxes, the overall entity-level tax rate on C-corporations is

$$\tau_t^c = \tau_t^{c,\mathrm{SL}} + \tau_t^{c,\mathrm{Fed}}.$$

Average Personal Tax Rates on Income from C-Corporations, $\tau^{e,c}$ and $\tau^{b,c}$

In addition to entity-level taxes, incomes distributed from C-corporations are subject to personal taxation. As described in the main text, we compute the corresponding tax rate as

$$\tau_t^{e,c} = \begin{array}{c}\text{share directly}\\ \text{owned}_t\end{array} \cdot \left(\begin{array}{c}\text{share short-}\\ \text{term ordinary}_t\end{array} \cdot \tau_t^o + \begin{array}{c}\text{share long-}\\ \text{term qualified}_t\end{array} \cdot \tau_t^q + \begin{array}{c}\text{share held}\\ \text{until death}_t\end{array} \cdot 0\% \right),$$

where τ_t^o is the average tax rate on short-term ordinary capital gains and dividends, and τ_t^q is the average tax rate on long-term qualified capital gains and dividends. For each year, we compute the share of corporate stocks directly owned by households as the ratio of share of equity held by households and non-profit organizations serving households over total corporate equity using data from FRED.[46] We build the share of profits realized through ordinary dividends and short-term capital gains on stocks directly owned by households using data from the IRS Individual Complete Report (Publication 1304, Table

[45] This series only span the period 1980-2013, with a missing data point in 1990, which we fill by linear interpolation. We assume that the share of net income of C-corporations in the total corporate sector has remained constant after 2013.

[46] The corresponding FRED series are HNOCEAQ027S and BOGZ1LM893064105Q, respectively

A) for the period 1990-2017 and the IRS SOI Tax Stats (Sales of Capital Assets Reported on Individual Tax Returns) for the period 1990-2012. Publication 1304 reports households' ordinary dividend income from corporate stocks, while the SOI Tax Stats reports the short-term capital gains on corporate stocks. The share of profits realized by households in the form of short-term gains or ordinary dividends can then be obtained by dividing the overall income from theses two sources by the net operating surplus of C-corporations.[47,48] We set "share short-term ordinary$_t$" to the average of the same variable over the period 1990-2012 for all years in our sample. The shares of profit realized long-term or until death are then computed assuming that half of the profits not realized in the short-term are never realized. This is in keeping with the findings reported in Table 14 of CBO (2006). Accordingly, the share of profits taxed at rate τ_t^q can be obtained as a residual, equal to half of the share of profits not taxed at the rate τ_t^o. The remaining share of profits is assumed to be unrealized until death, and subject to zero income taxation.

The average tax rates, τ_t^q and τ_t^o, are computed using data from the Office for Tax Analysis (OTA) for 1980–2014 (2019). Since both series exhibit trends over time, we extrapolate the data point for 2014 for the years 2015–2018. Ideally, τ_t^q should be the average marginal maximum tax rate for individuals realizing long-term capital gains and qualified dividends, and τ_t^o should be the average marginal ordinary income tax rate. However, these rates cannot be recovered from OTA data without detailed information on individual tax returns. We therefore proxy this quantity using the average tax rate on realized long-term capital gains provided by the OTA, which provides us with a measure for τ_t^q.[49] In addition to this average rate, the same source also reports the average long-term capital gains realized and the corresponding tax receipts. We combine this information with OTA data on total net capital gains and total taxes paid on net capital gains to obtain our measure of average taxes on short-term gains and ordinary dividends, τ_t^o.[50] In particular, we compute the tax

[47] In the notation above, this corresponds to the product

$$\begin{matrix}\text{share directly} \\ \text{owned}_t\end{matrix} \cdot \begin{matrix}\text{share short-} \\ \text{term ordinary}_t\end{matrix} .$$

[48] In practice, the share of profits taxed at ordinary rates is not limited to the short-term and ordinary dividends that accrue to the household from directly-owned corporate stocks. Capital gain distributions and IRA distributions—which originate from indirectly owned stocks—are also taxed at the ordinary rate, and constitute about 23% of realized profits over the period we considered. As a result, in our computations the share of profits taxed at ordinary income rates is 48%. Of this number, 25% comes form short-term gains and ordinary dividends from directly owned stocks (37% of stocks owned directly by households times 60% of profits realized in the form of short-term gains or ordinary dividends).

[49] Recovered at `https://www.treasury.gov/resource-center/tax-policy/tax-analysis/Documents/Taxes-Paid-on-Long-Term-Capital-Gains.pdf`.

[50] We recover this data at `https://www.treasury.gov/resource-center/tax-policy/tax-analysis/`

base for τ_t^o by subtracting realized long-term capital gains from total net capital gains. The relevant tax revenue is computed analogously, by subtracting total taxes paid on long-term capital gains from total taxes paid on total realized net capital gains. The ratio of these two quantities provides us with our estimate for τ_t^o.

The tax on interest income from C-corporations, $\tau^{b,c}$, is computed as explained in the main text. We obtained the share of fully taxable and temporarily deferred interest income and the average marginal tax rate on interest income for 2014 from Tables A-3 and A-4 of CBO (2014).

Average Tax Rates on Profits from S-Corporations, $\tau^{o,s}$ and $\tau^{b,s}$

Although S-corporations do not pay corporate income tax, the capital income from these corporations is taxed on the household side and the tax rate depends on how this income is realized. Long-term gains are taxed at the maximum marginal tax rate, while profits realized as short-term gains or net business income are taxed at the ordinary marginal tax rates. We obtained short-term capital gains from the sales of partnerships and S-corporations from the SOI Tax statistics Complete Year Data, Table 1 for years 1995-2011, and short-term gains to S-corporations in proportion to their share on the net income of partnerships plus S-corporations. We obtained profits realized through net business income from IRS Publication 4801, which provides yearly estimates for each item in IRS form 1040. In particular, taxpayers use columns (f)–(j) of Schedule E to register passive and non-passive income and losses from S-corporations and section 179 deductions.[51,52] These data are available for 2003-2017 and are reported in the yearly files of line-item estimates that can be downloaded from the IRS website.[53] This allows us to compute S-corporation profits realized in the form net business income as the sum net passive and active income minus the Section 179 deductions. We add this term to the realized short-term gains attributed to S-corporations as explained above, and divide this quantity by the net operating surplus attributable to S-corporations to obtain the short-term gain and business income share of S-coporation profits. Once again, we use IRS IBD Table 1 to attribute a fraction of NOSCORP$^{\mathrm{IRS}}$ to S-corporations in proportion to their share of the net income of corporations. The long-term gain share of S-corporation income is then simply obtained as the complement of the short-term and business income

`Documents/Taxes-Paid-on-Capital-Gains-for-Returns-with-Positive-Net-Capital-Gains.pdf`.

[51] Passive income and losses are reported for taxpayers who own S-corporations but do not participate actively to their administration. Active income and losses are for owners of S-corporation who actively administer the business or provide labor services to it.

[52] Section 179 of the tax code allows business owners to deduct investment expenses below a certain amount. The TCJA of 2017 set the maximum section 179 deduction at $1 million.

[53] `https://www.irs.gov/statistics/soi-tax-stats-individual-income-tax-returns-line-item-estimates`

share. We set this share equal to its average over the period 2003–2011 for all our sample. As mentioned in the previous section, the tax status of S-corporations is not recognized by all state and local government authorities. To account for these additional taxes, we computed the ordinary income tax rate for S-corporation owners as the sum of their personal income tax and the state and local business tax rate, $\tau^{c,\mathrm{SL}}$, described above. We estimate the average marginal income tax rate of S-corporation proprietors as the average income tax rate applied to short-term capital gains realized by owners of C-corporation stocks. Doing so amounts to assuming that the distribution of income of S-corporation proprietors coincides with that of C-corporation investors. This assumption is supported by Table A.4 in CBO (2014), which shows almost no difference between the average marginal tax rate on short-term capital gains of corporations and the average marginal tax rate on passthrough business profits. Finally, we calculate the tax rate on debt-financed investment analogously to C-corporations using the data provided in Table A.3 and A.4 in CBO (2014).

Assigning Depreciation Schedules

Table A.9 presents the sources we used to assign depreciation schedules to specific (fixed) asset types from BEA Table 2.7 of BEA FAT together with the resulting class lives and depreciation systems. Tables B.1-2 of IRS Publication 946 detail the class lives and the depreciation method according to the MACRS system, which applies to assets installed starting from the 1986 fiscal year. This allows us to match each of the fixed assets categories in BEA Table 2.7 to a class life. We then use the same class life to obtain the depreciation schedules according to the ACRS system from IRS Publication 534, which applies to property put in service in fiscal years 1981-1985.

Tables B.1-B.2 of IRS Publication 946 divide all types of capital into asset classes with corresponding class lives and depreciation methods. Tables B.1 collects asset classes for general-purpose capital (e.g., autos, trucks, office equipment). Table B.2 instead attributes class lives to the remaining asset classes according to the specific sector and application in which capital is employed, with considerable degree of detail. For example, all equipment used in the manufacturing of tobacco products (asset class 21.0) has a class life of 7 years, while the equipment used for knitting goods (asset class 22.1) has a class life of 5 years. Since BEA Table 2.7 does not allow us to distinguish the sector of application of many asset classes, we use the following strategy to build the crosswalk in Table A.9: Tables 6.A-B in the BEA NIPA Handbook contain the deflators (PPI's) that the BEA uses to build quantity indexes for each of the asset classes in BEA Table 2.7. This allows us to recover information on the underlying sectors of application for each type of capital, which we then match to the types of assets mentioned in the description of asset classes contained in Table B.2 of IRS Publication 946. For example, we match asset class 22.1 (equipment used for the production of knitting goods) and 22.4 (nonwoven fabrics) in Publication 946 to "Special Industry Machinery" in BEA Table 2.7, since the latter cites the PPI for textile machinery among the PPI's used to build the quantity index for "Special Industry Machinery". As this example illustrates, items in BEA Table 2.7 often correspond to multiple asset classes in Publication 946, each with potentially different class lives. We set the class life of each item in BEA Table 2.7 to the the mode of Publication 946 matching the class lives of asset classes, obtained as in the example above.[54]

The column "Sources P. 946" reports the items of Tables B.1-2 used to assign class lives. In some instances, Publication 946 refers to other sections of the tax code, or provides specific exceptions to the depreciation method that would apply following Tables B.1-2. When this is the case, the column "Sources P. 946" cites either the passage of Publication 946 listing the property under consideration, or the section of the tax code. We report the modal class life according to the Asset Depreciation Range system (ADR), the Accelerated Cost Recovery System (ACRS), and Modified Accelerated Cost Recovery System (MACRS). The ADR applies to assets installed in 1970-1980, ACRS to assets installed in 1981-1986, and MACRS applies to capital installed from 1986 onwards. MACRS consists of two depreciation systems, the General Depreciation System (GDS) and the Alternative Depreciation System (ADS), each prescribing different depreciation schedules. The ADS only applies to specific class lives and uses of property. However, the level of detail in BEA Fixed Asset (FA) Tables is not sufficient to attribute assets to this system precisely. We therefore follow the relevant GDS schedules when computing allowances and apply the MACRS system listed in the "GDS". "SL" denotes the straight-line method, while 200 and 150 denote the declining-balance (DB) methods with 200% and 150% accelerated depreciation, respectively. Finally, the column "HS" reports the classification in House and Shapiro (2008) when this is available.

We use GDS depreciation schedules with half-year convention from Appendix A of IRS Publication 946 (MACRS), and IRS Publication 534 (ACRS), and we apply the straight-line method for ADR, with the class lives listed in Tables B.1-2 of IRS Publication 946.[55] The MACRS provides schedules for assets installed in specific quarters or months of the year. We choose the half-year convention since we rely on annual data which does not allow us to

[54]In only one case—fabricated metal products—we chose the generic equipment class life of 7 years following House and Shapiro (2008), instead of the modal life of 20 that follows from our method.

[55]Using the class lives in Table B.1-2 and the straight-line method is likely to lead to some imprecision since the ADR system allowed substantial discretion in the choice of class lives, as much as ±20% from the baseline IRS class life. The choice of the depreciation method was also left to taxpayer discretion.

establish when capital was installed during the year.

Computing Total Discounts from Allowances

As discussed in the main text, depreciation allowances give rise to a discount on the purchase price of capital goods. This discount is given by the present discounted value of current and future tax payments that the business can deduct expensing the statutory allowance in each year. Assuming that the business in question correctly anticipates future changes in taxes and interest rate, and given a sequence of business tax rates $\{\tau_t\}$ and depreciation schedules $\{d_t^j\}$, tax discounts are given as:

$$\text{total discount from allowances}_t^j = d_t^j \cdot \tau_t + \sum_{s=0}^{\infty} d_{t+s+1}^j \cdot \tau_{t+s+1} \cdot \prod_{k=0}^{s} \frac{1 - d_{t+k}^j}{1 + r_{t+k+1}}.$$

Under our baseline assumption that depreciation rates and taxes are not changing, this expression simplifies to:

$$\text{total discount from allowances}_t^j = d_0^j \cdot \tau_t + \sum_{s=0}^{\infty} d_{s+1}^j \cdot \tau_t \cdot \prod_{k=0}^{s} \frac{1 - d_k^j}{1 + r_{t+k+1}}.$$

This term equals $\alpha_t \tau_t$ in the notation of the main text.

Computing Effective Taxes on Different Types of Capital

The final step to compute the average effective capital taxes reported in the main text consists involves averaging the effective taxes for the various (legal) form of organization and type of financing obtained above. To do, we first compute the share of debt and equity financing for each legal form of organization. We obtain the series for total equity and debt of the corporate and non-corporate sector from FRED.[56] This allows us to directly compute the share of capital financed through debt and equity in the non-corporate sector. We follow the CBO (2006, 2014) and attribute debt and equity to C-corporations and S-corporations. The IRS SOI provides income tax returns for all corporations for 1994-2013. We compute total equity as the sum of the capital stock, paid-in capital, retained earnings and adjustment to shareholders' equity, minus the treasury stock cost. We then compute the share of total corporate equity in the tax returns that relates to S-corporations, and attribute to them the relevant part of the aggregate stock of corporate equity (about 4% of the total). The remaining fraction is attributed to C-corporations. We assigned debt to

[56] Series BCNSDODNS, NCBEILQ027S, NNBCMIA, TNWBSNNB.

the two forms of organization in proportion to their share in total interest deductions of corporations, as reported by the IRS SOI. The share of debt financing for each legal form of organization is therefore given by its stock of debt over the sum of debt and equity, while its complement measures equity financing. Since the series exhibit trends, we use closest-neighbor extrapolation to fill in the missing data for the years before 1994 and after 2013. Armed with these shares, we can compute effective taxes on capital for each legal form of organization. Finally, we construct the economy-wide average effective capital tax by weighing the tax rate of each legal form of organization by its share of net business income in each year. The source for net business income by form of organization is once again the IRS IBD.

Sources for the Computation of the Effective Labor Tax Rate, τ^ℓ

We calculate the effective labor tax rate, τ^ℓ as the weighted average of labor income and payroll taxes and the wedge introduced by imperfect valuation of employer-provided pension and health insurance contributions:

$$\tau^\ell = \frac{\text{salaries} \cdot (\tau^h + \tau^p) + \text{benefits} \cdot (1 - \varphi)}{\text{compensation}}.$$

Line 2 in NIPA Tables 6.11B-D contains the value of employers' contributions for employee pension and health insurance funds, while line 2 of BEA NIPA Table 1.10 provides the total compensation of employees in the economy. Subtracting employers' contributions from total compensations gives us total salaries. We use the average personal income tax rate of the bottom 95% of the income distribution from IRS SOI Tax Stats for 1986–2017 as our measure of the personal income tax rate, τ^h.[57] The payroll tax rate, τ^p, is computed as the sum of the Old-Age, Survivors, and Disability Insurance (OASDI) and Medicare's Hospital Insurance (HI) rates for each year, that we retrieve from the Social Security Administration Website.[58]

Other Sources

We obtained investment in private fixed assets by type from BEA FAT 2.7. We computed the depreciation rate of each type of fixed assets in each year, dividing current-cost depreciation from BEA FAT Table 2.4 by the current-cost stock of each type from Table 2.4. The source for fixed asset price changes is BEA FAT Table 2.8. When computing effective capital taxes by category for equipment, software and nonresidential structures, we weigh the effective

[57] "Individual Statistical Tables by Tax Rate and Income Percentile", Table 2.
[58] `https://www.ssa.gov/OACT/ProgData/taxRates.html`.

capital tax constructed for each type of asset by the share of investment in each category as listed in BEA FAT Table 2.7. As mentioned in the text, we use Moody's Seasoned AAA Corporate Bond Yield from FRED (series AAA) deflated by the CPI for all urban consumers (CPIAUCSL). For robustness, we also used allowances and effective tax series using the lending interest rate from the World Bank adjusted for inflation using the GDP deflator (World Bank indicator FR.INR.RINR). This has a minimal impact on our results, slightly raising the present discounted value of depreciation allowances. The average real return on S&P 500 stocks over the period 1957–2008 is computed deflating the FRED series SP500 by the CPI for all urban consumers.

Table A.8: Components for the computation of capital taxation

Variable Name	Full Name	Components/Formula	Elaboration on:	Notes
NOSPCU	Net operating surplus of private enterprises	Includes: net interest payments of domestic businesses; net transfer payments; proprietors' income; rental income of persons; corporate profits gross of corporate taxes; all variables are adjusted for inventory valuation and capital consumption.	BEA Table 1.10	
NOSCORP	Net operating surplus of corporations	Component of the above	BEA Table 1.14	
CFCPCU, CFC-CORP	Consumption of fixed capital of private enterprises, corporations	—	BEA Tables 1.1.10, 1.1.14	Represents *economic* depreciation of the capital stock
OS*	*Gross* operating surplus of private enterprises, corporations	NOS* + CFC*	BEA Tables 1.1.10, 1.1.14	Represents the *economic* tax base before allowing for depreciation
OSPUE	*Gross* operating surplus of private *unincorporated* enterprises	OSPCU - OSCORP	—	—
CCAll*	Capital consumption allowances for PUE, corporations	—	BEA data from FRED.	—

Table A.9: Class lives and depreciation schedules for equipment, structures, and intellectual property products

Type	Sources P. 946	ADR	ACRS	MACRS	HS	GDS
Computers and peripheral equipment	0.12	6	5	5	5	200
Communication equipment	36, 48.2, 48.37, 48.42–.45, 48.13, 00.11, 48.35–.36,48.38–42, 48.31, 48.34	10	5	7	5	200
Medical equipment and instruments	sec. 168(B)iv,		5	5	7	200
Nonmedical instruments	36,48.37, 48.39, 48.44, 26.1, 37.2	6	5	7	7	200
Photocopy and related equipment	0.13,	6	5	5	5	200
Office and accounting equipment	0.13,	6	5	5	5	200
Fabricated metal products	48.42, section 168(C), 49.12, 40.52, 49.11, 49.13, 49.21, 49.221, 49.3, 49.4, 51	6	10	7	7	150
Engines and turbines	6	5	7	15	200	
Computers and peripheral equipment	0.12	6	5	5	5	200
Metalworking machinery	34.01, 37.12, 33.21, 37.33, 33.2, 33.4, 34.0, 35.0, 37.11, 37.2, 37.31, 37.41, 37.42	12	5	7	7	200

Type	Sources P. 946	ADR	ACRS	MACRS	HS	GDS
Special industry machinery, n.e.c.	20.5, 30.11, 30.21, 32.11, 22.1, 22.3,22.4, 23.0, 24.1, 24.3, 28.0, 36, 36.1, 57.0 , 20.4, 22.2, 22.5, 24.2, 24.4, 26.1, 26.2, 27.0, 30.1, 30.2, 31.0, 32.1, 32.3, 79.0 80.0, 13.3, 20.1–.3, 32.2	10	5	7	7	200
General industrial, including materials handling, equipment	00.241,00.242[59]	6	5	5	7	200
Electrical transmission, distribution, and industrial apparatus	48.38, 48.31, , 0.4, 49.11, 49.13, 49.14	10	5	20	7	150
Trucks, buses, and truck trailers	00.23–00.242	4	5	5	5	200
Light trucks (including utility vehicles)	0.241,	4	3	5	5	200
Other trucks, buses, and truck trailers	00.23,00.242,	6	5	5	5	200
Autos	0.22,	3	3	5	5	200
Aircraft	0.21,	6	5	5	7	200
Ships and boats	0.28,	10	5	10	10	150
Railroad equipment	40.1,	14	5	7	7	200
Furniture and fixtures	0.11,	10	5	7		200
Agricultural machinery	1.1,	10	5	7	7	150
Construction machinery	15,	6	5	5	5	200
Mining and oilfield machinery	13, 13.1, 10,13.2,	6	5	5	7	200

[59] Exclusion of general purpose from most sectoral class lives of conveyor belts and general-purpose tools.

Type	Sources P. 946	ADR	ACRS	MACRS	HS	GDS
Service industry machinery	57, 79–80,	9	5	7	7	200
Electrical equipment, n.e.c.	Ch.4, p.28	6	5	7	7	200
Other nonresidential equipment	Ch.4, p.28	6	5	7	7	200
Residential equipment	Ch.4, p.28					
Structures			15–18–19			SL
Nonresidential structures[60]	Ch. 4 p. 31			39[61]		
Commercial and health care	Ch. 4 p. 31			39	39	
Manufacturing structures	Ch. 4 p. 31			39	39	
Electric structures	49.12,49.15, 49.11, 49.13, 49.14	20		20	20	150
Other power structures	49.23, 49.24, 49.25	14		15	15	150
Communication	48.14,	15		15	15	150
Mining exploration, shafts, and wells						
Petroleum and natural gas	13.0, 13.1, 13.2	6	10	5	5	200
Mining structures	10,	10	10	7	5	200
Farm structures				20	20	150
Residential structures				27.5		SL

[60] Applies to religious, education, lodging, amusement and other nonresidential structures that are not explicitly mentioned below

[61] As per publication 946, structures put in service before 1994 should have a useful life of 31.5 years. For simplicity, we use 39 for all years.

Type	Sources P. 946	ADR	ACRS	MACRS	HS	GDS
Nonresidential intellectual property products[62]	section 197			15		SL
Software					5	
Prepackaged	Ch. 1, p. 10, not sec.197			3		SL
Custom	Ch. 1, p. 10, not sec.197			3		SL
Own account	sec. 167(f)1			15 years		SL
Research and development	item 5, sec 197			15		SL

[62] Applies to all intellectual property products not explicitly mentioned below.