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Abstract

Adding (1) the endogenous labor supply of workers, (2) fiscal policy instruments, and (3) monopolistic competition to Berg et al.'s (2018) general equilibrium model of automation, we study how automation (i.e., robots and artificial intelligence) affects the efficacy of redistribution policy. Using the consumption equivalent welfare gain developed by Domeij and Heathcote (2004) and assuming a 50 percent increase in robot-augmented technology shock, we derive the optimal tax rates for various tax policy instruments in the steady state of the model economy calibrated for the United States. We find that the optimal capital income tax rate is 20 percent. Another finding is that the zero tax rate on the wage income of unskilled workers is an optimal tax policy. We also find that the optimal tax rates on robots and consumption are dependent on the preference of the government. Finally, we find that the Pareto-efficient optimal tax system is characterized as a combination of a 15.9 percent rate on capital income tax and a zero tax rate on unskilled workers' income. Our analysis contributes to the literature on optimal taxation in the automated age.

Keywords: Automation, Fiscal Policy, Optimal Taxation, Capital Income Tax, Labor Income Tax, Consumption Tax, Robot Tax, Social Welfare, Dynamic General Equilibrium

JEL Classification Codes: H21, H24, H25, H30, E25, O30, O40, C68

Introduction

How does automation affect the redistributive mechanism of fiscal policy? We study the optimal fiscal policy to address inequality caused by automation, as automation brings welfare benefits to capitalists and skilled workers but welfare loss to unskilled workers (Berg et al 2021). In our paper, we define "automation" as a technology that includes the categories of "robot" and "artificial intelligence (AI)." As automation technology advances rapidly in the economy, new types of capital—e.g., robotics and forms of intangible capital that include software for AI—accumulate in the economy, in addition to traditional capital. The accumulation of intangible capital increases productivity growth (Nakatani 2021). In this environment, optimally sharing gains from automation depends on redistributive fiscal policy working primarily through taxation policy that maximizes social welfare. We contribute to the literature on optimal taxation, which historically has three streams: optimal labor income taxation, optimal capital income taxation, and the optimal combination of multiple tax instruments, as illustrated below.

Optimal labor income taxation theory was established by Mirrlees (1971), who found a linear structure to the optimal marginal income tax schedule with a zero marginal tax rate for the top-income earner. Stern (1976) studied optimal linear income taxation, finding that the maximum marginal tax rate on income depends on the distribution of income and the government's preference. Stiglitz (1982) found the optimal negative marginal tax rate on high-ability individuals, which does depend on different individuals not being perfect substitutes for one another in production. Tuomala (1984) calculated the optimal nonlinear income tax rates and showed that the marginal tax rate could be regressive. In contrast, Diamond (1998) found a U-shaped optimal tax structure. Dahan and Strawczynski (2000) demonstrated that Diamond's U-shaped pattern depends on a linear utility of consumption. These results from the literature imply an economic intuition that an equity (efficiency) consideration drives an upward-sloping (downward-sloping) marginal tax schedule. Our question is what the optimal labor income tax rate becomes in the presence of automation in the economy. Intuitively, since low-skilled workers suffer from automation, the optimal nonlinear labor income tax schedule is likely to be progressive in the automated age.

In the field of optimal capital income taxation, Chamley (1986) and Judd (1985) found that the optimal capital income tax rate is zero in the steady state because capital income taxation is harmful to capital accumulation. Judd (2002) found that the optimal capital tax may be negative under imperfect competition because the exploding distortions caused by markups in the capital market need to be reduced with subsidies. Straub and Werning (2020) recently overturned the conclusion of Chamley-Judd's zero capital income taxation in the long run, proving that the long-run tax on capital is positive and significant when the intertemporal elasticity of substitution of capitalists is below one. In the automated economy, capitalists gain too much from technological progress, so the zero tax rate on capital income might not be optimal, depending on societal preference, the intertemporal elasticity of substitution, and imperfect competition. Alternatively, the deadweight loss caused by capital income taxation could be magnified in the automated economy, as redistributing the gains from robot-augmented technological progress might be preferred to imposing detrimental taxes on capital accumulation that deter technological revolution. Our research is the first study to examine optimal capital income taxation in the context of automation.

The last stream in the theory of optimal tax literature regards choosing a combination of various tax rates. Atkinson and Stiglitz (1976) developed a theorem regarding uniform commodity tax under nonlinear income taxation. However, this Atkinson-Stiglitz theorem was overturned by Naito (1999), who used Stolper and

Samuelson's (1941) theorem to show that a nonuniform commodity tax can Pareto-improve welfare even under nonlinear income taxation if the production side of the economy is considered. Thus, we use the general equilibrium model taking into account the production side, but we stick to the uniform commodity tax rate since we only consider a single product. Rather, from the viewpoint of the optimal tax policy mix in an era of automation, we analyze the optimal combination of the capital income tax rate and nonlinear labor income tax rate because this practical tax policy mix has not been previously explored in the automation literature, and we find strong results for these two taxes policies, as we will show later in this paper.

A new literature on optimal taxation for automation, i.e., robots and AI, has been recently growing (Merola 2022). Zhang (2019) found that taxing robots can improve wage inequality between skilled and unskilled workers in the face of automation. Costinot and Werning (2022) found that the optimal robot tax decreases as the process of automation deepens. Guerreiro et al. (2022) studied the combination of robot tax and the Mirrleesean labor tax, and they found that taxing robots is optimal only when routine workers are active in the labor force. Thuemmel (2022) found that a robot tax or subsidy is optimal depending on its price, while most welfare gains can be achieved by adjusting the income tax. However, all such literature only studies the optimal tax mix on labor and robots. Jaimovich et al. (2021) studied job retraining programs, universal basic income, transfers, and nonlinear income tax reform as potential policy options to address inequality caused by automation. However, they did not study other types of taxes or their various combinations as an optimal tax system. Therefore, in this paper, we study comprehensive fiscal policy packages that include various types of taxes in the automated economy.

We introduce (i) fiscal policy instruments, (ii) endogenous labor supply decisions of workers, and (iii) nominal friction caused by monopolistic competition into the automation model developed by Berg et al. (2018). We include monopolistic competition as introduced by Dixit and Stiglitz (1977) because one important feature of automation is that monopolistic big tech firms enjoy monopolistic rents as a result of network effects in reality, and the Dixit-Stiglitz model is the most commonly used framework for this analysis. Next, we elaborate on the detailed model setting and calibration of parameters.

Model

The economy consists of firms, workers (skilled and unskilled), owners of capital (or capitalists), and the government. The population shares of skilled workers, unskilled workers, and capitalists are denoted by N_S, N_L, and N_C, respectively. Without a loss of generality, we normalize the total population to be one:$N_S + N_L + N_C = 1$.

We assume that N_C is constant over time. The ratio of skilled workers to total workers is denoted by ϕ, and it is dependent on public spending on education G, i.e., $\phi = \phi(G)$. In reality, this value is related to government job training programs that convert unskilled workers into skilled workers.

There are three types of firms: intermediate goods firms, final goods firms, and wholesale firms. The production of intermediate goods requires the combination of traditional capital K_d, automation-related capital (which comprises robots and the intangible capital related to AI) Z_d, skilled labor S_d, and unskilled labor L_d.

The final goods are produced by combining a continuum of differentiated goods indexed by j, according to the Dixit-Stiglitz aggregator:

$$Y = \left[\int_0^1 y_{j,t}^{\frac{\epsilon-1}{\epsilon}}\, dj\right]^{\frac{\epsilon}{\epsilon-1}}, \tag{1}$$

where y_j is the quantity of output sold by wholesale firm j and ϵ is the elasticity of substitution across the differentiated goods, satisfying $1 < \epsilon < \infty$. The final goods producer maximizes profits as subject to the above production technology, taking the input price $p_{j,t}$ and the final goods price P_t as given. The profit maximization problem yields the following demand function:

$$y_{j,t} = \left(p_{j,t}/P_t\right)^{-\epsilon} Y_t \quad , \tag{2}$$

and the aggregate price index $P_t = \left[\int_0^1 p_{j,t}^{1-\epsilon}\, dj\right]^{\frac{1}{1-\epsilon}}$. Without a loss of generality, we normalize the output price to be one, i.e., $P_t = 1$.

There is a unit measure for wholesale firms. Wholesalers buy homogeneous goods from intermediate goods firms and transform them into heterogeneous goods, which are then sold to final goods firms, and their production technology is linear: $y_{j,t} = Q_{j,t}$. We assume that wholesalers are owned by capitalists and have a monopolistic power to set the price of the goods they sell. This assumption reflects the fact that big tech companies (e.g., Google, Apple, Facebook, and Amazon) enjoy monopolistic rent in the age of automation/AI/big data. Given this, the representative wholesaler chooses $Q_{j,t}$ and $p_{j,t}$ to solve the following problem:

$$\max \Pi_{j,t} = \int_0^1 \left(p_{j,t} y_{j,t} - \theta_t Q_{j,t}\right) dj, \tag{3}$$

which is subject to the demand function (1). θ_t is the price of intermediate goods. Then, we have

$$p_{j,t} = \left(\frac{\epsilon}{\epsilon-1}\right)\theta_t, \tag{4}$$

and by normalizing the price of final goods to unity, the above equation gives

$$\theta_t = (\epsilon-1)/\epsilon. \tag{5}$$

Note that the markup can be expressed as $markup_t = 1/\theta_t$.

We assume that the markup is constant. For readers who are interested in the endogenous markup model, please see Berg et al. (2021). We introduce markup because large firms (e.g., big tech companies) can take advantage of owning the platform and other digitalization-related networks, which makes their marginal costs lower than the average costs. This is because the costs of constructing such a network can be an entry barrier for other companies, which leads to both large market shares and markups.

The intermediate goods firm produces output by using capital K_d, robots Z_d, skilled labor S_d, and unskilled labor L_d, according to the following triple-nested CES production function:

$$Q_t = \mathrm{A}\left[a^{\frac{1}{\sigma_1}} H_t^{\frac{\sigma_1-1}{\sigma_1}} + (1-a)^{\frac{1}{\sigma_1}} V_t^{\frac{\sigma_1-1}{\sigma_1}}\right]^{\frac{\sigma_1}{\sigma_1-1}}, \tag{6}$$

where $A = A_0(G)^{\xi}$ is an aggregate productivity that is dependent on public spending on education G, and

$$V_t = \left[e^{\frac{1}{\sigma_2}} L_{d,t}^{\frac{\sigma_2-1}{\sigma_2}} + (1-e)^{\frac{1}{\sigma_2}} (b_t Z_{d,t})^{\frac{\sigma_2-1}{\sigma_2}}\right]^{\frac{\sigma_2}{\sigma_2-1}}, \tag{7}$$

$$H_t = \left[f^{\frac{1}{\sigma_3}} S_{d,t}^{\frac{\sigma_3-1}{\sigma_3}} + (1-f)^{\frac{1}{\sigma_3}} K_{d,t}^{\frac{\sigma_3-1}{\sigma_3}}\right]^{\frac{\sigma_3}{\sigma_3-1}} \tag{8}$$

where σ_1 is the elasticity of substitution between composite inputs H and V, σ_2 is the elasticity of substitution between robots and unskilled workers, and σ_3 is the elasticity of substitution between capital and skilled labor. Depending on the values of these elasticities, this production technology allows for high substitution between unskilled labor and robots and complementarity between skilled labor and capital (Krusell et al 2000) as well as between skilled labor and robots.

The intermediate goods firm maximizes its profit by choosing capital, robots, and two types of labor, subject to equations (6)-(8) according to

$$\max_{K_d, Z_d, S_d, L_d} \theta_t Q_t - r_{K,t} K_{d,t} - r_{Z,t} Z_{d,t} - w_{S,t} S_{d,t} - w_{L,t} L_{d,t},$$

where r_K and r_Z are the rental rates of capital and robots, respectively, and w_S and w_L are the wage rates for skilled and unskilled workers, respectively. Then, the first-order conditions of this problem are

$$\theta_t \frac{\partial Q_t}{\partial K_{d,t}} = r_{K,t}, \qquad \theta_t \frac{\partial Q_t}{\partial Z_{d,t}} + Q_t \frac{\partial \theta_t}{\partial Z_{d,t}} = r_{Z,t},$$

$$\theta_t \frac{\partial Q_t}{\partial S_{d,t}} + Q_t \frac{\partial \theta_t}{\partial S_{d,t}} = w_{S,t}, \qquad \theta_t \frac{\partial Q_t}{\partial L_{d,t}} + Q_t \frac{\partial \theta_t}{\partial L_{d,t}} = w_{L,t}$$

Further elaboration reduces the above to the following relatively simple conditions:

$$\theta_t \frac{\partial Q_t}{\partial K_{d,t}} = r_{K,t}, \qquad \theta_t \frac{\partial Q_t}{\partial Z_{d,t}} \left[1 - \frac{x}{s_{Z,t}}\right] = r_{Z,t}, \tag{9}$$

$$\theta_t \frac{\partial Q_t}{\partial S_{d,t}} \left[1 + \frac{x}{s_{S,t}} \frac{S_{d,t}}{S_{d,t}+L_{d,t}}\right] = w_{S,t}, \quad \theta_t \frac{\partial Q_t}{\partial L_{d,t}} \left[1 + \frac{x}{s_{L,t}} \frac{L_{d,t}}{S_{d,t}+L_{d,t}}\right] = w_{L,t}. \tag{10}$$

Workers consume all of their income. The representative skilled worker's utility function is calculated by preferences as proposed by Greenwood et al. (1988) to abstract from income effects:

$$U(C_S, S) = \frac{1}{1-\sigma_S}\left(C_{S,t} - \Phi_S \frac{S_t^{1+\mu_S}}{1+\mu_S}\right)^{1-\sigma_S}, \tag{11}$$

where C_S is the consumption of skilled workers and S is the labor supply. $\Phi_S > 0$ is a measure of the disutility parameter of working, and μ_S is the inverse of the Frisch elasticity. Since we know from Diamond (1998) that the optimal marginal tax rate at the bottom of skill distribution becomes higher when there are no income effects on utility function, we prefer this specification of utility function to examine whether the progressive labor income tax rate is still optimal in this robust setting. The budget constraint of the skilled worker is

$$(1+\tau_c) C_{S,t} = \left(1 - \tau_{w_S}\right) w_{S,t} S_t + \kappa, \tag{12}$$

where τ_c is the consumption tax rate, τ_{w_S} is the tax rate on skilled workers' income, and κ is the universal lump-sum transfer. The skilled worker chooses C_S and S to maximize the utility function in (11) subject to the budget constraint in (12). The first-order conditions correspond to equation (12), and

$$\Phi_S S_t^{\mu_S} = \frac{1-\tau_{w_S}}{1+\tau_c} w_{S,t}.$$

Similarly, the unskilled worker's problem can be written as

$$\max_{C_L,L} U(C_L, L) = \frac{1}{1-\sigma_L}\left(C_{L,t} - \Phi_L \frac{L_t^{1+\mu_L}}{1+\mu_L}\right)^{1-\sigma_L}, \tag{13}$$

which is subject to

$$(1+\tau_c)C_{L,t} = \left(1-\tau_{w_L}\right) w_{L,t} L_t + \kappa + s_L, \tag{14}$$

where τ_{w_L} is the tax rate on unskilled workers' income and s_L is the trageted transfer to unskilled workers. The first-order conditions are modelled by equation (14) and

$$\Phi_L L_t^{\mu_L} = \frac{1-\tau_{w_L}}{1+\tau_c} w_{L,t}.$$

Capitalists own firms, they do not work, and they save to smooth consumption over time. These savings are invested in automation and traditional capital. This setup helps to characterize the "winner-take-all" aspect of automation as well as the fact that "the rise of the top one percent is likely very tied up with technology." The representative capitalist chooses consumption c_t, investment in capital I_K, and investment in robots I_Z to maximize

$$\max_{C,I_K,I_Z} \sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\sigma_C}}{1-\sigma_C} \quad , \tag{15}$$

subject to the following budget constraint and the capital and robot accumulation equations:

$$(1+\tau_c)C_t + I_{K,t} + I_{Z,t} = (1-\tau)\left[r_{K,t}K_t + r_{Z,t}Z_t\right] + (1-\tau_\theta)(1-\theta)\frac{Q_t}{N_C} + \kappa - \tau_Z Z_t, \tag{16}$$

$$K_{t+1} = (1-\delta_K)K_t + I_{K,t}, \tag{17}$$

and

$$Z_{t+1} = (1-\delta_Z)Z_t + I_{Z,t}, \tag{18}$$

where β is the discount factor, δ_K is the depreciation rate of capital, δ_Z is the depreciation rate of the robots, τ is the capital income tax rate, τ_θ is the tax rate on markup, and τ_Z is the robot tax rate. We assume $\tau_\theta = \tau$ throughout the paper, i.e., the tax on markup is collected as a part of capital income taxation.

The first-order conditions of the capitalists' maximization problem include the following Euler equations:

$$\frac{\lambda_t}{\beta\lambda_{t+1}} = (1-\tau)\frac{\partial Q_{t+1}}{\partial K_{d,t+1}} + (1-\delta_K), \quad \text{and} \quad \frac{\lambda_t}{\beta\lambda_{t+1}} = (1-\tau)\frac{\partial Q_{t+1}}{\partial Z_{d,t+1}} - \tau_Z + (1-\delta_Z),$$

which at the initial steady state correspond to

$$1 = \beta\left[(1-\tau)\frac{\partial Q}{\partial K_d} + 1 - \delta_K\right], \quad \text{and} \quad 1 = \beta\left[(1-\tau)\frac{\partial Q}{\partial Z_d} + 1 - \delta_Z - \tau_Z\right].$$

The government has multiple instruments (taxes and expenditures) with which to implement fiscal policy, subject to a balanced budget in each period. The government budget constraint is given by

$$
\begin{aligned}
\mathrm{G} + \sum_{i=L,S,C} N_i\kappa + N_L s_L \\
&= N_C\big[\tau\{r_{K,t}K_t + r_{Z,t}Z_t\} + \tau_c C_t + \tau_Z Z_t\big] + \tau_\theta(1-\theta)Q_t + N_S\big[\tau_{w_S}w_{S,t}S_t + \tau_c C_{S,t}\big] \\
&+ N_L\big[\tau_{w_L}w_{L,t}L_t + \tau_c C_{L,t}\big].
\end{aligned}
$$

The goods market is in equilibrium when the supply of firms equals the demand of capitalists, workers, and government:

$$
Q_t = N_c\big(C_t + I_{K,t} + I_{Z,t}\big) + N_s C_{S,t} + N_L C_{L,t} + G_t.
$$

The labor markets are in equilibrium when the labor demand is equal to the labor services supplied by workers:

$$
S_{d,t} = N_S S_t,
$$

and

$$
L_{d,t} = N_L L_t.
$$

Similarly, the capital and robot markets are in equilibrium when

$$
K_{d,t} = N_C K_t,
$$

and

$$
Z_{d,t} = N_C Z_t.
$$

The welfare gain for skilled workers Δ_S as defined by Domeij and Heathcote (2004) satisfies the following equation:

$$
U\big(C_{S,t}^R, S_t^R\big) = U\Big((1+\Delta_S)C_{S,t}^{NR}, S_t^{NR}\Big)
$$

where equilibrium consumption is represented by C_S^R in the case of tax reform and C_S^{NR} in the case of no tax reform. The same applies to superscripts of labor supply. The above equation can be rewritten as follows:

$$
\frac{1}{1-\sigma_S}\left\{C_{S,t}^R - \Phi_S\frac{(S_t^R)^{1+\mu_S}}{1+\mu_S}\right\}^{1-\sigma_S} = \frac{1}{1-\sigma_S}\left\{(1+\Delta_S)C_{S,t}^{NR} - \Phi_S\frac{(S_t^{NR})^{1+\mu_S}}{1+\mu_S}\right\}^{1-\sigma_S}
$$

$$
\therefore \Delta_S = \left[C_{S,t}^R - \Phi_S\left\{\frac{\left(S_t^R\right)^{1+\mu_S}}{1+\mu_S} - \frac{\left(S_t^{NR}\right)^{1+\mu_S}}{1+\mu_S}\right\}\right]\Big/C_{S,t}^{NR} - 1.
$$

The same calculation yields a welfare gain for unskilled workers Δ_L:

$$
\Delta_L = \left[C_{L,t}^R - \Phi_L\left\{\frac{\left(L_t^R\right)^{1+\mu_L}}{1+\mu_L} - \frac{\left(L_t^{NR}\right)^{1+\mu_L}}{1+\mu_L}\right\}\right]\Big/C_{L,t}^{NR} - 1.
$$

The welfare gain for capitalists Δ_C satisfies the following equation:

$$\sum_{t=0}^{\infty} \beta^t \frac{(C_t^R)^{1-\sigma_C}}{1-\sigma_C} = \sum_{t=0}^{\infty} \beta^t \frac{\left((1+\Delta_C)C_t^{NR}\right)^{1-\sigma_C}}{1-\sigma_C}$$

$$\therefore \Delta_C = \left\{\frac{(C_0^R)^{1-\sigma_C}+\beta(C_1^R)^{1-\sigma_C}+\beta^2(C_2^R)^{1-\sigma_C}+\cdots}{(C_0^{NR})^{1-\sigma_C}+\beta(C_1^{NR})^{1-\sigma_C}+\beta^2(C_2^{NR})^{1-\sigma_C}+\cdots}\right\}^{\frac{1}{1-\sigma_C}} - 1.$$

Social welfare based on population shares, as introduced by Acemoglu and Autor (2011), is defined as follows:

$$\Delta = N_S\Delta_S + N_L\Delta_L + N_C\Delta_C.$$

A utilitarian government uses equal weights for aggregating individual welfare gains:

$$\Delta_{Utilitarian} = (\Delta_S + \Delta_L + \Delta_C)/3.$$

Calibration

The model is calibrated to match the U.S. economy. Table 1 summarizes the parameter values in the initial steady state. Following Berg et al. (2018), we set the steady-state discount rate to 0.5 percent (i.e., discount factor $\beta = 0.995$). The depreciation rates are the same for both capital and robots ($\delta_K = \delta_Z = 0.05$).

The shares in production of the composite input H, unskilled labor, and skilled labor are calibrated to match a capital income share of 0.35, an unskilled income share of 0.31, a skilled income share of 0.30, and a robot income share of 0.04. This yields a = 0.800, e = 0.988, and f = 0.058. Following Berg et al. (2018), we set the elasticity of substitution between H and V to 0.67 and the elasticity of substitution between skilled labor and capital to 0.335. We set the elasticity of substitution between unskilled labor and robots to 1.9, as estimated by DeCanio (2016). The markup is 1.19 according to Barkai (2020).

For the inverse of the Frisch elasticity, we set $\mu_L = 2$ and $\mu_S = 2$, which are taken from the intensive margin as per Chetty et al. (2011). This means that the Frisch elasticity of both unskilled and skilled labor is 0.5, which is the median value suggested in the literature. Following Berg et al. (2018), we set the intertemporal elasticity of substitution to 0.5 (i.e., $\sigma = 2$), which is the same as the mean estimated by Havranek et al. (2015). The disutility parameter of working for unskilled workers is set by targeting the steady state working hours to be one-third (i.e., eight hours per day). The observed wage dispersion between skilled and unskilled workers—i.e., $w_S/w_L = 2$—is used to specify the parameter of the skilled worker's disutility of working.

The population is normalized to 1, and the share of capitalists is one percent. The share of skilled workers to total workers depends on public spending on education $\phi = \phi_0 G^{\gamma}$. Peralta and Roitman (2018) report that a four percentage point shift from unskilled to medium/high skilled workers costs 1-3 percent of GDP, based on education costs in the U.S. On this basis, we set $\gamma = 0.22$. We calibrate ϕ_0 to match the 55 percent share of unskilled workers, as reported by Acemoglu and Autor (2011). Education spending also affects the level of total factor productivity (TFP). Thus, we assume that $A = A_0(G)^{\xi}$, where ξ is the elasticity of TFP to education spending. As there are no direct empirical counterparts of ξ, we postulate that a one percentage point increase in education spending raises TFP by one percent. A_0 is set to normalize the output to one.

We calibrate the tax rates based on the latest 2014 U.S. data from the national accounts. The income tax rate (capital income as well as labor income for skilled and unskilled workers) is calibrated to match 13.17 percent of GDP, which is the actual ratio of the (individual and corporate) income tax revenue as a percentage of GDP. The consumption tax rate is calibrated to match the actual ratio of 4.48 percent that represents the indirect tax revenue (taxes on goods and services and on international trade) as a share of GDP. As a result, we obtain 14.4 percent of the (capital and labor) income tax rate and 6.8 percent of the consumption tax rate. Public spending on education is set to 0.041, which is consistent with U.S. data.

Results

We restrict our attention to steady states and put 50 percent of the shock to the productivity of automation-related capital. We are tackling a long-run issue, and we are not even sure what the actual timeline of the robot shock is, so the value added of computing the transition path is negligible. We use two social welfare measures because the optimal fiscal policy is dependent on societal preference (Gueorguiev and Nakatani 2021). The simulation results are shown in Tables 2-6.

A capital income tax hike improves the welfare of unskilled workers by transferring what is mainly the capitalists' gains from automation to unskilled workers (Table 2). High capital income tax rates reduce the welfare of both capitalists and skilled workers by reducing the accumulation of capital that complements skilled labor. The optimal capital income tax rate is 20 percent according to Acemoglu and Autor's (2011) population share. In contrast, a utilitarian government prefers a zero capital income tax rate, as the welfare gain for capitalists is very large, which is consistent with the famous findings of Chamley (1986) and Judd (1985).[1]

The robot tax deters the accumulation of automation-related capital and limits gains from automation. This lowers the welfare of capitalists while bringing redistributive benefits from automation to unskilled workers through transfers (Table 3). A utilitarian government does not want to impose a robot tax because it only lowers social welfare through a large welfare loss for capitalists. On the other hand, social welfare based on population shares as presented by Acemoglu and Autor (2011) increases as the robot tax rate increases. This calls for careful consideration of the government's aversion to inequality in the formulation of the tax on automation-related capital (i.e., robot tax).

A reduction in the tax rate on unskilled workers' wage income improves social welfare through an interesting channel (Table 4). Unskilled workers actually lose welfare because the lower price of unskilled labor increases labor demand by firms, which in turn reduces the utility of unskilled workers . This disutility effect from increased labor more than offsets the positive utility gained from the increased consumption for unskilled workers. The opposite holds for skilled workers. Capitalists also benefit from cheap unskilled labor

[1] Atesagaoglu and Yazici (2021) also found that it is optimal not to tax capital income if the declining labor share is accompanied by a rising capital share, although they abstract from redistributive concerns.

when the income tax rate for unskilled workers is lowered from that of the status quo. As a result, the optimal tax rate is zero in both the utilitarian case and the case of Acemoglu and Autor (2011). This is a strong outcome in the sense that it is optimal for any type of government. The zero tax rate on unskilled workers' income combined with transfers to them indicates that the policy for providing basic support to the most vulnerable workers can be an option for governments in the automated economy, although unskilled workers still have to increase their cheap labor supply and suffer from its disutility.

The optimal consumption tax rate differs across different types of government (Table 5). For a utilitarian government, the optimal tax rate on consumption is zero because the welfare gains for skilled workers and capitalists achieved through their increased consumption exceed the welfare loss for unskilled workers. In contrast, a government whose preference is based on realistic population shares as suggested by Acemoglu and Autor (2011) prefers a higher consumption tax rate, as the unskilled workers' welfare gain from the redistribution policy that is financed by the consumption tax dominates the change in social welfare, reflecting the higher population share of unskilled workers than that in the Utilitarian context.

In the final analysis, we study the combination of two tax policy instruments to find the Pareto-efficient optimal tax policy reform in an era of automation. Based on our aforementioned results assuming a single tax policy instrument, we found that both a 20 percent rate of capital income tax and a zero tax rate on unskilled labor can achieve optimality in the context of a realistic government's preference. We examine whether the combination of these two tax reforms can demonstrate Pareto-improving welfare, although the optimal capital income tax rate might differ from a single tax reform, as we combine it with a zero income tax rate for unskilled workers to avoid the welfare loss for capitalists to satisfy Pareto optimality.

Table 6 shows that, in the context of a zero tax rate on unskilled workers' income, the Pareto-efficient capital income tax rate lies between 15.5-15.9 percent, and the Pareto-efficient "optimal" capital income tax rate is 15.9 percent (Note that capitalists' welfare slightly decreases when the capital income tax rate is 16 percent). In contrast, the Pareto-efficient optimal capital income tax rate for a utilitarian government is slightly lower at 15.5 percent. These findings on the Pareto-efficient optimal tax mix are a reflection of the Tinbergen principle, which states that the number of policy instruments should match the number of policy objectives. For example, in the case of monetary and macroprudential policies, a combination of the interest rate policy and the reserve requirement policy can attain the two objectives of economic stability and financial stability (Nakatani 2016). In our case of fiscal and redistribution policy, to achieve each of the two objectives of improving the welfare of unskilled workers and allowing the gains from automation to benefit skilled workers and capitalists, we require two tax policy instruments: a capital income tax and tax on unskilled workers' income. Our findings concerning the optimal tax mix of reducing taxes on unskilled labor and raising capital income taxes reinforce the argument forwarded by Acemoglu et al. (2020), who suggested that the current U.S. tax system is biased against labor and favors capital; therefore, reducing excessive subsidies to capital and reducing payroll taxes would enhance welfare.

Conclusion

We studied the optimal fiscal policy in the automated economy and make the following six conclusions. First, we find that there is no Pareto-efficient fiscal policy instrument if we only change a single tax rate. Second, the optimal capital income tax rate is found to be 20 percent. Third, a utilitarian government does not want to impose a robot tax, while a government whose preference is based on realistic population shares for workers and capitalists could benefit from a robot tax. Fourth, removing the personal income tax for unskilled workers increases the social welfare of society. Fifth, consumption tax can be a redistributive policy tool in the automated economy, while this is not the case for a utilitarian government that places more weight on winners (i.e., capitalists and skilled workers). Finally, we found that the Pareto-efficient optimal tax reform is a combination of a capital income tax rate of 15.9 percent and a zero tax rate on unskilled workers' income. This optimal capital income tax rate is 1.5 percentage points higher than the status quo economy and approximately 1 percentage point higher than the statutory tax rate of 15 percent in the U.S. Thus, the policy implication is that an approximately 1 to 1.5 percent increase in the capital income tax rate could improve social welfare in a Pareto-efficient way if the tax reform is supplemented by removing income tax for unskilled workers in an age of automation.

References

Acemoglu, D., & D. Autor. 2011. Skills, Tasks, and Technologies: Implications for Employment and Earnings. *Handbook of Labor Economics* 4B: 1043-1171.

Acemoglu, D., A. Manera, & P. Restrepo. 2020. Does the US Tax Code Favor Automation? *Brookings Papers on Economic Activity*, Spring 2020: 231-285.

Atesagaoglu, O., & H. Yazici. 2021. Optimal Taxation of Capital in the Presence of Declining Labor Share. *CESifo Working Paper* 9101.

Atkinson, A., & J. Stiglitz. 1976. The Design of Tax Structure: Direct versus Indirect Taxation. *Journal of Public Economics* 6 (1–2): 55-75.

Barkai, S. 2020. Declining Labor and Capital Shares. *Journal of Finance* 75 (5): 2421-2463.

Berg, A., L. Bounader, N. Gueorguiev, H. Miyamoto, K. Moriyama, R. Nakatani, & L. Zanna. 2021. For the Benefit of All: Fiscal Policies and Equity-Efficiency Trade-offs in the Age of Automation. *IMF Working Paper* 21/187.

Berg, A. E. Buffie, & L. Zanna. 2018. Should We Fear the Robot Revolution? (The Correct Answer is Yes). *Journal of Monetary Economics* 97: 117-148.

Chamley, C. 1986. Optimal Taxation of Capital Income in General Equilibrium with Infinite Lives. *Econometrica* 54 (3): 607-622.

Chetty, R., A. Guren, D. Manoli, & A. Weber. 2011. Are Micro and Macro Labor Supply Elasticities Consistent? A Review of Evidence on the Intensive and Extensive Margins. *American Economic Review* 101 (3): 471-475.

Costinot, A., & I Werning. 2022. Robots, Trade, and Luddism: A Sufficient Statistic Approach to Optimal Technology Regulation. *Review of Economic Studies*, forthcoming.

Dahan, M., & M. Strawczynski. 2000. Optimal Income Taxation: An Example with a U-Shaped Pattern of Optimal Marginal Tax Rates: Comment. *American Economic Review* 90 (3): 681-686.

DeCanio, S. 2016. Robots and Humans—Complements or Substitutes? *Journal of Macroeconomics* 49: 280-291.

Diamond, P. 1998. Optimal Income Taxation: An Example with a U-Shaped Pattern of Optimal Marginal Tax Rates. *American Economic Review* 88 (1): 83-95.

Dixit, A., & J. Stiglitz. 1977. Monopolistic Competition and Optimum Product Diversity. *American Economic Review* 67 (3): 297-308.

Domeij, D. & J. Heathcote. 2004. On the Distributional Effects of Reducing Capital Taxes. *International Economic Review* 45 (2): 523-554.

Greenwood, J., Z. Hercowitz, & G. Huffman. 1988. Investment, Capacity Utilization, and the Real Business Cycle. *American Economic Review* 78 (3): 402-417.

Gueorguiev, N., & R. Nakatani. 2021. Sharing the Gains of Automation: The Role of Fiscal Policy. *IMF Blog*, November 18.

Guerreiro, J., S. Rebelo, & P. Teles. 2022. Should Robots Be Taxed? *Review of Economic Studies* 89 (1): 279-311.

Havranek, T., R. Horvath, Z. Irsova, & M. Rusnak. 2015. Cross-Country Heterogeneity in Intertemporal Substitution. *Journal of International Economics* 96: 100-118.

Jaimovich, N., I. Saporta-Eksten, H. Siu, & Y. Yedid-Levi. 2022. The Macroeconomics of Automation: Data, Theory, and Policy Analysis. *Journal of Monetary Economics* 122: 1-16.

Judd, K. 1985. Redistributive Taxation in a Simple Perfect Foresight Model. *Journal of Public Economics* 28 (1): 59-83.

Judd, K. 2002. Capital-Income Taxation with Imperfect Competition. *American Economic Review* 92 (2): 417-421.

Krusell, P., L. Ohanian, J. Ríos-Rull, & G. Violante. 2000. Capital-Skill Complementarity and Inequality: A Macroeconomic Analysis. *Econometrica* 68 (5): 1029-1053.

Merola, R. 2022. Inclusive Growth in the Era of Automation and AI: How Can Taxation Help? *Frontiers in Artificial Intelligence* 5:867832.

Mirrlees, J. 1971. An Exploration in the Theory of Optimum Income Taxation. *Review of Economic Studies*, 38 (2): 175–208.

Naito, H. 1999. Re-Examination of Uniform Commodity Taxes under a Non-Linear Income Tax System and Its Implication for Production Efficiency. *Journal of Public Economics* 71 (2): 165-188.

Nakatani, R. 2016. Twin Banking and Currency Crises and Monetary Policy. *Open Economies Review* 27(4): 747-767.

Nakatani, R. 2021. Total Factor Productivity Enablers in the ICT Industry: A Cross-Country Firm-Level Analysis. *Telecommunications Policy* 45 (9): 102188.

Peralta, A., & A. Roitman. 2018. Technology and the Future of Work. *IMF Working Paper* 18/207.

Stern, N. 1976. On the Specification of Models of Optimum Income Taxation. *Journal of Public Economics* 6 (1-2): 123-162.

Stiglitz, J. 1982. Self-Selection and Pareto Efficient Taxation. *Journal of Public Economics* 17 (2): 213-240.

Stolper, W. & P. Samuelson. 1941. Protection and Real Wages. *Review of Economic Studies* 9 (1): 58-73.

Straub, L., & I. Werning. 2020. Positive Long-Run Capital Taxation: Chamley-Judd Revisited. *American Economic Review* 110 (1): 86-119.

Thuemmel, U. 2022. Optimal Taxation of Robots. *Journal of the European Economic Association*, forthcoming.

Tuomala, M. 1984. On the Optimal Income Taxation: Some Further Numerical Results. *Journal of Public Economics* 23 (3): 351-366.

Zhang, P. 2019. 2019. Automation, Wage Inequality and Implications of a Robot Tax. *International Review of Economics & Finance*, 59: 500-509.

Table 1. Calibration

Parameter	Description	Value	Source or Target
σ_1	Elasticity of substitution between composite capital and composite labor	0.67	Berg et al. (2018)
σ_2	Elasticity of substitution between unskilled labor and robots	1.9	DeCanio (2016)
σ_3	Elasticity of substitution between skilled labor and capital	0.335	Berg et al. (2018)
a	Share parameter of composite labor in production	0.800	Berg et al. (2018)
e	Share parameter of unskilled labor in composite labor	0.988	Berg et al. (2018)
f	Share parameter of skilled labor in composite capital	0.058	Berg et al. (2018)
σ_L	The inverse of intertemporal elasticity of substitution for unskilled workers	2	Berg et al. (2018)
σ_S	The inverse of intertemporal elasticity of substitution for skilled workers	2	Berg et al. (2018)
σ_C	The inverse of intertemporal elasticity of substitution for capitalists	2	Berg et al. (2018)
μ_L	The inverse of Frisch elasticity of unskilled labor supply	2	Chetty et al. (2011)
μ_S	The inverse of Frisch elasticity of skilled labor supply	2	Chetty et al. (2011)
Φ_L	Disutility of unskilled work	10.4	L=1/3 (i.e., 8 hours)
Φ_S	Disutility of skilled work	59.2	w_s/w_l=2
β	Discount factor	0.995	Berg et al. (2018)
δ_K	Depreciation rate of capital	0.05	Berg et al. (2018)
δ_Z	Depreciation rate of robots	0.05	Berg et al. (2018)
$\emptyset_0$	Parameter for population share function	0.909	Acemoglu and Autor (2011)
ξ	Elasticity of TFP to education spending	0.22	Peralta and Roitman (2018)
A_0	Initial total factor productivity	0.279	Berg et al. (2018)
$\tau, \tau_{w_L}, \tau_{w_S}$	Tax rate on income from skilled/unskilled labor or capital	0.144	U.S. data (13.17 percent of GDP)
τ_c	Tax rate on consumption	0.068	U.S. data (4.48 percent of GDP)
ϵ	The elasticity of substitution (implied markup is 1.19)	6.263	Barkai (2020)

Table 2. Social Welfare Change under the Optimal Capital Income Tax Rate

Tax Rate	Individual Welfare			Social Welfare	
	Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
0%	-15.69%	9.88%	32.56%	8.92%	-3.82%
5%	-9.46%	6.50%	20.86%	5.97%	-2.05%
10%	-4.04%	3.06%	9.56%	2.86%	-0.74%
15%	0.52%	-0.44%	-1.34%	-0.42%	0.07%
19%	3.53%	-3.29%	-9.75%	-3.17%	0.36%
20%	4.19%	-4.01%	-11.82%	-3.88%	0.38%
21%	4.81%	-4.73%	-13.86%	-4.59%	0.37%
25%	6.90%	-7.65%	-21.87%	-7.54%	0.13%

Note: A red result is the optimal capital income tax rate for Acemoglu and Autor’s (2011) social weights, and a blue result is the optimal capital income tax rate for a utilitarian government.

Table 3. Social Welfare Change under the Optimal Robot Tax Rate

Tax Rate	Individual Welfare			Social Welfare	
	Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
1%	2.90%	0.00%	-7.45%	-1.52%	1.50%
5%	14.50%	0.00%	-37.27%	-7.59%	7.52%
10%	29.00%	0.00%	-74.53%	-15.18%	15.05%
15%	43.50%	0.00%	-111.80%	-22.77%	22.57%
20%	58.00%	0.00%	-149.07%	-30.36%	30.09%
25%	72.50%	0.00%	-186.34%	-37.95%	37.61%

Note: The policy experiment starts with a 1% tax rate on robots because 0% is the same as the status quo tax regime.

Table 4. Social Welfare Change under the Optimal Unskilled Wage Income Tax Rates

Tax Rate	Individual Welfare			Social Welfare	
	Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
0%	-0.95%	2.02%	3.50%	1.52%	0.42%
5%	-0.54%	1.35%	2.34%	1.05%	0.33%
10%	-0.21%	0.64%	1.12%	0.52%	0.18%
15%	0.00%	0.00%	-0.16%	-0.05%	0.00%
20%	0.16%	-0.87%	-1.50%	-0.74%	-0.32%

Notes: A red result is the optimal unskilled wage income tax rate for Acemoglu and Autor’s (2011) social weights, and a blue result is the optimal unskilled wage income tax rate for a utilitarian government. The purple unskilled wage income tax rate is optimal for both welfare criteria.

Table 5. Social Welfare Change under the Optimal Consumption Tax Rate

Tax Rate	Individual Welfare			Social Welfare	
	Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
0%	-9.21%	6.84%	6.84%	1.49%	-1.90%
5%	-2.36%	1.75%	1.75%	0.38%	-0.49%
10%	3.88%	-2.88%	-2.88%	-0.63%	0.80%
15%	9.57%	-7.10%	-7.10%	-1.54%	1.98%
20%	14.79%	-10.97%	-10.97%	-2.38%	3.06%
25%	19.59%	-14.53%	-14.53%	-3.16%	4.05%

Note: A blue result is the optimal consumption tax rate for a utilitarian government.

Table 6. Social Welfare Change under the Optimal Capital Income Tax Rate with a Zero Tax Rate on Unskilled Workers' Income

Tax Rate	Individual Welfare			Social Welfare	
	Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
15%	-0.38%	1.57%	2.13%	1.11%	0.51%
15.4%	0.00%	1.28%	1.25%	0.84%	0.58%
15.5%	0.00%	1.21%	1.03%	**0.75%**	0.55%
15.6%	0.15%	1.14%	0.81%	0.70%	0.60%
15.7%	0.24%	1.06%	0.60%	0.63%	0.61%
15.8%	0.33%	0.99%	0.38%	0.57%	0.62%
15.9%	0.41%	0.92%	0.16%	0.50%	**0.63%**
16%	0.50%	0.85%	0.00%	0.45%	0.65%
20%	3.66%	-2.09%	-8.65%	-2.36%	0.98%

Notes: The pink-colored results are Pareto-efficient tax rates. Among these Pareto-efficient results, a red result is the Pareto-efficient optimal capital income tax rate for Acemoglu and Autor's (2011) social weights, and a blue result is the Pareto-efficient optimal capital income tax rate for a utilitarian government.