Motivation

▶ Automation raises productivity but displaces workers and lowers their earnings

▶ Increasing adoption has fueled an active policy debate (Atkison, 2019; Acemoglu et al, 2020)

▶ No optimal policy results that take into account frictions faced by displaced workers

▶ Two literatures can justify taxing automation.

  (i) Reallocation is frictionless or absent

    Tax automation

    Guerreiro et al 2017; Costinot-Werning 2018

  (ii) Govt. has preference for redistribution

  (i) Automation/reallocation are efficient

    Tax capital (long-run)

    Aiyagari 1995; Conesa et al. 2002

  (ii) Improve efficiency in economies with IM

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1. Improve efficiency in economies with IM
2. Worker displacement/reallocation absent
Take worker displacement seriously. **How should we respond to automation?**

1. Recognize that displaced workers face two important frictions:
   - Slow reallocation: workers face mobility barriers and may go through unempl./retraining (Davis-Haltiwanger, 1999; Jacobson et al, 2005; Lee-Wolpin, 2006; Alvarez-Shimer, 2011)
   - Imperfect credit markets: workers have limited ability to borrow against future incomes (Jappelli et al, 2010; Chetty, 2008)

2. Incorporate frictions in a model with endog. automation and heterogeneous agents

3. Theoretical results:
   - Interaction between frictions gives rise to inefficient automation
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4. Quantitative: gross flows + idiosync. risk → welfare gains from slowing down automation
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Outline

Environment

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
Continuous time $t \geq 0$
Continuous time $t \geq 0$

<table>
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Resource constraint

$$Z_c(t)(x) \Delta = G \ast \mu_A, \mu_N; \alpha \phi h \mu h t = Z 1 \{h(x) = h\} \xi d \pi t$$
### Environment

**Continuous time** $t \geq 0$

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**Occupations**

$h = A$ (share $\phi$, degree $\alpha \geq 0$) or $h = N$

$$F^h(\mu) = \begin{cases} F^*(\mu; \alpha) & \text{if } h = A \\ F(\mu) \equiv F^*(\mu; 0) & \text{if } h = N \end{cases}$$
Environment

Continuous time $t \geq 0$

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Final Good Producer

$$G^* (\mu^A, \mu^N; \alpha) \equiv G \left( \left\{ F^h(\mu^h) \right\} \right)$$

(gross complements)

Workers

Reallocation afterwards $U_0 = E_0 Z \exp (-\rho t) c_1 - \sigma t dt$

Resource constraint $Z c_t(x) d \Lambda = G^* (\mu^A, \mu^N; \alpha)$

Example
Environment

Continuous time $t \geq 0$

**Occupations**

$h = A$ (share $\phi$, degree $\alpha \geq 0$) or $h = N$

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$\partial_{\mu^A} G^*(\mu^A, \mu^N; \alpha) \downarrow$ in $\alpha$ (labor-displacing)

$G^*(\mu^A, \mu^N; \alpha)$ concave in $\alpha$ (costly)

**Workers**

Workers $x = \{s, h, \xi\}$ (age, occupation, prod.)
Environment

Continuous time $t \geq 0$

**Occupations**

$$h = A \text{ (share } \phi, \text{ degree } \alpha \geq 0) \text{ or } h = N$$

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---

**Workers**

$x = \{s, h, \xi\}$ (age, occupation, prod.)

$$(\mu_t^A, \mu_t^N) \begin{cases} = 1 & \text{in } t = 0 \\ \text{Reallocation afterwards} \end{cases}$$
Environment

Continuous time \( t \geq 0 \)

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\]

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Environment

Continuous time $t \geq 0$

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Workers

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$$U_0 = \mathbb{E}_0 \left[ \int \exp(-\rho t) \frac{c^1_t - \sigma}{1 - \sigma} dt \right]$$

Resource constraint

$$\int c_t(x) \, d\Lambda = G^* (\mu^A, \mu^N; \alpha)$$

$$\phi^h\mu^h_t = \int 1_{\{h(x) = h\}} \xi \, d\pi_t$$
Reallocations frictions

- Reallocation of existing workers is **costly** (Kambourov-Manovskii, Violante, Costinot-Werning)

1. **Permanent cost**: productivity loss $\theta$ due to skill-specificity

\[
\xi_t = \begin{cases} 
\lim_{\tau \uparrow t} \xi_{\tau} & \text{if } h'_t(x) = h \\
(1 - \theta) \times \lim_{\tau \uparrow t} \xi_{\tau} & \text{otherwise}
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- Reallocation of existing workers is slow (Davis-Haltiwanger, Alvarez-Shimer). Two reasons:

  2. **Random opportunities**: Workers can move across occupations with intensity $\lambda$

  3. **Unemployment/retraining spells**: Enter when moving, and exit at rate $\kappa$
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  2. **Random opportunities**: Workers can move across occupations with intensity $\lambda$

  3. **Unemployment/retraining spells**: Enter when moving, and exit at rate $\kappa$

- Arrival of new workers is **slow** (Rebelo et al., Adão et al.). Rate $\chi$. Choose any occupation.
Outline

Environment

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
First Best Problem

Ex post problem  |  Ex ante problem

\[ \int_{T_{FB0}}^{\infty} e^{-\rho t} u' c_N t \Delta t = 0 \]

where \( \Delta t \equiv \frac{1}{1 - e^{-\kappa (t - T_{FB0})}} \)

\[ \text{Cost} = \text{Skill loss} + \text{unemp} \]

\[ \text{MPL gap} \]

\[ \text{is the IRF of } Y \text{ to reallocation} \]

\[ Z + \int_{0}^{\infty} e^{-\rho t} u' c_A t \Delta^\circ t \, dt = 0 \]

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Ex post problem

- Reallocate labor and distribute output
- Close MPLs gap. Stop reallocation at $T_{FB}^0$
  (No OLG case)

Ex ante problem

$$Z + \int_{0}^{\infty} e^{-\rho t} u' c N_t \Delta t dt = 0$$

where

$$\Delta t \equiv \left(1 - \theta \right)^{1 - e^{-\kappa (t - T_{FB}^0)}}$$

Cost = Skill loss + unemployment

$Y_N t - Y_A t$ is the IRF of $Y$ to reallocation
First Best Problem

****Ex post problem****

- Reallocate labor and distribute output
- Close **MPLs** gap. Stop reallocation at $T_0^{FB}$
  (No OLG case)

$$
\int_{T_0^{FB}}^{+\infty} e^{-\rho t} u'(c_t^N) \Delta_t dt = 0
$$

where

$$
\Delta_t \equiv (1 - \theta) \left(1 - e^{-\kappa(t - T_0^{FB})}\right) \frac{Y_t^N - Y_t^A}{\Delta_t^{\text{MPL gap}}}
$$

is the IRF of $Y$ to reallocation

---

*Cost = Skill loss + unemp*
First Best Problem

**Ex post problem**

- Reallocate labor and distribute output
- Close MPLs gap. Stop reallocation at $T_{0}^{FB}$ (No OLG case)

\[
\int_{T_{0}^{FB}}^{+\infty} e^{-\rho t} u' \left( c_t \right) \Delta_t dt = 0
\]

where

\[
\Delta_t \equiv (1 - \theta) \left( 1 - e^{-\kappa(t-T_{0}^{FB})} \right)^{\text{MPL gap}} \left[ Y_t^N - Y_t^A \right]^{\text{Cost = Skill loss + unemp}}
\]

is the IRF of $Y$ to reallocation

**Ex ante problem**

- Choose degree of automation $\alpha^{FB}$
- Reduce $C$ today, expand $Y$ tomorrow

\[
\int_{T_{0}^{FB}}^{+\infty} e^{-\rho t} u' \left( c_t \right) \Delta_t dt = 0
\]
First Best Problem

Ex post problem

▶ Reallocate labor and distribute output
▶ Close MPLs gap. Stop reallocation at $T^{FB}_0$ (No OLG case)

\[
\int_{T^{FB}_0}^{+\infty} e^{-\rho t} u' \left( c_t^N \right) \Delta_t dt = 0
\]

where

\[\Delta_t \equiv (1 - \theta) \left( 1 - e^{-\kappa (t - T^{FB}_0)} \right) \left\{ \frac{\nu_t^N - \nu_t^A}{\nu_t^A} \right\} \]

is the IRF of $Y$ to reallocation

Ex ante problem

▶ Choose degree of automation $\alpha^{FB}$
▶ Reduce $C$ today, expand $Y$ tomorrow

\[
\int_{0}^{+\infty} e^{-\rho t} u' \left( c_t^A \right) \Delta_t^* dt = 0
\]

where

\[\Delta_t^* \equiv \frac{\partial}{\partial \alpha} G^* \left( \mu_t^A, \mu_t^N; \alpha^{FB} \right)\]

is the IRF of $Y$ to automation (net of cost)
Outline

Environment

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
Decentralized Choices

Firms

Workers

Equity priced by unconstrained workers

No arbitrage

\[ Q_t = \exp(-R_t^0 r_s ds) \]
Decentralized Choices

**Firms**

Choose automation \( \alpha \) + labor demand \( \mu_t \)

\[
\max_{\{\alpha, \mu_t\}} \int_0^{+\infty} Q_t \Pi_t (\mu_t; \alpha) \, dt
\]

**Workers**
Decentralized Choices

Firms

Choose automation $\alpha +$ labor demand $\mu_t$

$$\max_{\{\alpha, \mu_t\}} \int_0^{+\infty} Q_t I_t(\mu_t; \alpha) \, dt$$

Workers

Choose cons. $c_t$ and labor supply $\mu_t$
Decentralized Choices

**Firms**
Choose automation $\alpha$ + labor demand $\mu_t$

$$\max_{\{\alpha, \mu_t\}} \int_0^{+\infty} Q_t \Pi_t(\mu_t; \alpha) \, dt$$

**Workers**
Choose cons. $c_t$ and labor supply $\mu_t$

**Assets:** riskless bonds

Workers not insured against automation risk
Decentralized Choices

Firms

Choose automation $\alpha +$ labor demand $\mu_t$

$$\max_{\{\alpha, \mu_t\}} \int_0^{+\infty} Q_t \Pi_t(\mu_t; \alpha) \, dt$$

Workers

Choose cons. $c_t$ and labor supply $\mu_t$

**Assets:** riskless bonds

Workers not insured against automation risk

$x = \{a, s, h, \xi\}$ (bonds, age, occ., prod.)
# Decentralized Choices

## Firms

Choose automation $\alpha$ + labor demand $\mu_t$

$$\max_{\{\alpha, \mu_t\}} \int_0^{+\infty} Q_t \Pi_t(\mu_t; \alpha) \, dt$$

## Workers

Choose cons. $c_t$ and labor supply $\mu_t$

**Assets**: riskless bonds

Workers not insured against automation risk

$$x = \{a, s, h, \xi\} \text{ (bonds, age, occ., prod.)}$$

$$da_t(x) = [Y^*_t(x) + (r_t + \chi)a_t(x) - c_t(x)] \, dt$$
Decentralized Choices

**Firms**

Choose automation $\alpha$ + labor demand $\mu_t$

$$\max_{\{\alpha, \mu_t\}} \int_0^{+\infty} Q_t \Pi_t (\mu_t; \alpha) \, dt$$

**Workers**

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**Assets:** riskless bonds

Workers not insured against automation risk

$$x = \{a, s, h, \xi\} \text{ (bonds, age, occ., prod.)}$$

$$da_t (x) = \left[ \mathcal{Y}_t^* (x) + (r_t + \chi) a_t (x) - c_t (x) \right] dt$$

**Borrowing friction**

$$a_t (x) \geq a \text{ for some } a \leq 0$$
Decentralized Choices

**Firms**

Choose automation $\alpha$ + labor demand $\mu_t$

$$\max_{\{\alpha, \mu_t\}} \int_0^{+\infty} Q_t II_t (\mu_t; \alpha) \, dt$$

No arbitrage $\rightarrow Q_t = \exp \left( - \int_0^t r_s \, ds \right)$

Equity priced by unconstrained workers

**Workers**

Choose cons. $c_t$ and labor supply $\mu_t$

**Assets**: riskless bonds

Workers not insured against automation risk

$$x = \{a, s, h, \xi\} \text{ (bonds, age, occ., prod.)}$$

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Quantitative Analysis
**Proposition. (Failure of FWT)**

1. The laissez-faire equilibrium is inefficient if and only if reallocation frictions \((\lambda, \kappa)\) and borrowing frictions \((a)\) are such that \(a^*(\lambda, \kappa) < a \leq 0\) for threshold \(a^*(\cdot)\).
**Proposition.** (Failure of FWT)

1. The laissez-faire equilibrium is inefficient if and only if reallocation frictions \((\lambda, \kappa)\) and borrowing frictions \((a)\) are such that \(a^* (\lambda, \kappa) < a \leq 0\) for threshold \(a^*(\cdot)\).

2. The threshold \(a^* (\lambda, \kappa) < 0\) if and only if reallocation is slow \((1/\lambda \text{ or } 1/\kappa > 0)\).
Failure of the First Welfare Theorem

**Proposition.** (Failure of FWT)

1. The laissez-faire equilibrium is inefficient if and only if reallocation frictions \((\lambda, \kappa)\) and borrowing frictions \((a)\) are such that \(a^* (\lambda, \kappa) < a \leq 0\) for threshold \(a^*(\cdot)\).

2. The threshold \(a^* (\lambda, \kappa) < 0\) if and only if reallocation is slow \((1/\lambda\) or \(1/\kappa > 0)\).

▶ **Interaction** between reallocation and borrowing frictions \(\rightarrow\) inefficient automation
Failure of the First Welfare Theorem

Distortions at the laissez-faire

\[ \lambda \]

\[ \frac{1}{\lambda_0} \]

\[ \frac{1}{\lambda} \]

Efficient cases: instant realloc. (Costinot-Werning) or no borrowing frictions (Guerreiro et al)

Workers expect income to improve as they reallocate \( \rightarrow \) Motive for borrowing

Inefficiency

\[ a^* (\lambda) \]

Slow reallocation

Tight constraint

\[ a \uparrow \]
Failure of the First Welfare Theorem

Distortions at the laissez-faire

Efficient cases: instant realloc. (Costinot-Werning) or no borrowing frictions (Guerreiro et al)
Failure of the First Welfare Theorem

Distortions at the laissez-faire

Average income

Workers expect income to improve as they reallocate → Motive for borrowing
Why Is Automation Inefficient?

Compare two optimality conditions for automation

(Firm at laissez-faire)  (Valuing like displaced workers would)

\[
\int_{0}^{+\infty} e^{-\rho t} \frac{u'(c_{N,t}^N)}{u'(c_{0,0}^N)} \Delta_t^* \, dt = 0
\]

\[
\int_{0}^{+\infty} e^{-\rho t} \frac{u'(c_{A,t}^A)}{u'(c_{0,0}^A)} \Delta_t^* \, dt = 0
\]

where \( \Delta_t^* \) is the IRF of \( Y \) to automation.
Why Is Automation Inefficient?

- Compare two optimality conditions for automation

(Firm at laissez-faire) (Valuing like displaced workers would)

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\int_0^{+\infty} e^{-\rho t} \frac{u'(c_{0,t})}{u'(c_{0,0})} \Delta^*_t dt = 0
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\[
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\]

- No borrowing constraints \( \frac{u'(c_{0,t})}{u'(c_{0,0})} = \frac{u'(c_{A,t})}{u'(c_{A,0})} \) → First best = Laissez-faire
Why Is Automation Inefficient?

- Compare two optimality conditions for automation

(Firm at laissez-faire)  (Valuing like displaced workers would)

$$\int_{0}^{+\infty} e^{-\rho t} \frac{u'(c_{0,t}^N)}{u'(c_{0,0}^N)} \Delta_t^* dt = 0$$

$$\int_{0}^{+\infty} e^{-\rho t} \frac{u'(c_{0,t}^A)}{u'(c_{0,0}^A)} \Delta_t^* dt = 0$$

- Borrowing constraints
  
  $$\frac{u'(c_{0,t}^N)}{u'(c_{0,0}^N)} > \frac{u'(c_{0,t}^A)}{u'(c_{0,0}^A)} \rightarrow$$  
  First best $\neq$ Laissez-faire
Why Is Automation Inefficient?

- Compare two optimality conditions for automation

\[
\int_0^{+\infty} e^{-\rho t} \frac{u'(c_{0,t})}{u'(c_{0,0})} \Delta_t^* dt = 0
\]

\[
\int_0^{+\infty} e^{-\rho t} \frac{u'(c_{A,t})}{u'(c_{A,0})} \Delta_t^* dt = 0
\]

- Borrowing constraints \( \frac{u'(c_{0,t})}{u'(c_{0,0})} > \frac{u'(c_{A,t})}{u'(c_{A,0})} \) → First best ≠ Laissez-faire

Firms fail to internalize that displaced workers have a limited ability to smooth consumption while they reallocate.
Outline

Environment

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
Optimal policy

How should a government respond to automation? Depends on the tools available.
How should a government respond to automation? Depends on the tools available

- Suppose: tax on automation $\tau^\alpha +$ arbitrary transfers/taxes to redistribute
Optimal policy

How should a government respond to automation? Depends on the tools available

▶ Suppose: tax on automation $\tau^\alpha +$ arbitrary transfers/taxes to redistribute

▶ Wedge between first best and laissez-faire optimality condition

$$\tau^\alpha = \int_0^{+\infty} e^{-\rho t} \left( \frac{u'(c_{N_0,t})}{u'(c_{0,0})} - \frac{u'(c_{A_0,t})}{u'(c_{0,0})} \right) \Delta^*_t \, dt$$
How should a government respond to automation? Depends on the tools available

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$$\tau^\alpha = \int_0^{+\infty} e^{-\rho t} \left( \frac{u'(c_{0,t}^N)}{u'(c_{0,0}^N)} - \frac{u'(c_{0,t}^A)}{u'(c_{0,0}^A)} \right) \Delta_t^* dt$$

When is $\tau^\alpha = 0$? Redistributive tools $\rightarrow$ alleviate borrowing cons. and close MRS gap
Optimal policy

How should a government respond to automation? Depends on the tools available.

- Suppose: tax on automation $\tau^\alpha +$ arbitrary transfers/taxes to redistribute.

- Wedge between first best and laissez-faire optimality condition:

  $$\tau^\alpha = \int_0^{+\infty} e^{-\rho t} \left( \frac{u'(c_{0,t}^N)}{u'(c_{0,0}^N)} - \frac{u'(c_{0,t}^A)}{u'(c_{0,0}^A)} \right) \Delta_t^* dt$$

1. Worker/time-specific lump sum transfers → implement any first best (SWT holds).

   Info requirements? Take-up? Political? (Piketty-Saez, 2013; Guerreiro et al., 2017; Costinot-Werning, 2018)
Optimal policy

How should a government respond to automation? Depends on the tools available

▶ Suppose: tax on automation $\tau^\alpha +$ arbitrary transfers/taxes to redistribute

▶ Wedge between first best and laissez-faire optimality condition

$$\tau^\alpha = \int_0^{+\infty} e^{-\rho t} \left( \frac{u'(c^N_0, t)}{u'(c^N_0, t)} - \frac{u'(c^A_0, t)}{u'(c^A_0, t)} \right) \Delta^*_t dt$$

2. **Symmetric lump sum transf.** (UBI) $\rightarrow$ govt. borrows for workers $\rightarrow$ restore efficiency

Second best tools: tax automation (ex ante) + labor market interventions (ex post)

No social insurance for now, reintroduced in quantitative model
Constrained Ramsey problem

- **Second best tools**: tax automation (*ex ante*) + labor market interventions (*ex post*)
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- Tractability: hand-to-mouth workers ($a \to 0$), no OLG ($\chi = 0$)
Constrained Ramsey problem

- **Second best tools**: tax automation *(ex ante)* + labor market interventions *(ex post)*
  No social insurance for now, reintroduced in quantitative model

- **Tractability**: hand-to-mouth workers *(a → 0)*, no OLG *(χ = 0)*

- **Primal problem**: control automation \(α\) and reallocation \(T_0\)

\[
\max_{\{\alpha, T_0, \mu_t, c_t\}} \sum_h \phi^h \eta^h \int_0^{+\infty} \exp(-\rho t) u(c^h_t) \, dt
\]

subject to workers’ budget constraints, the law of motion of labor, firms choosing labor optimally, and market clearing.
Constrained inefficiency (regardless of Pareto weights)

Government’s optimality conditions to **automate** \((\alpha)\) and **reallocate** \((T_0)\)

\[
\int_0^{+\infty} \exp(-\rho t) \frac{u'(c_{0,t})}{u'(c_{0,0})} \Delta^*_t dt = -\Phi^*(\alpha^{SB}, T_0^{SB}; \eta)
\]

\[
\int_{T_0^{SB}}^{+\infty} \exp(-\rho t) \frac{u'(c_{0,t})}{u'(c_{0,0})} \Delta_t dt = -\Phi(\alpha^{SB}, T_0^{SB}; \eta)
\]

\{ laissez-faire \}

\{ pecuniary externalities \}
Constrained inefficiency (regardless of Pareto weights)

Government’s optimality conditions to automate $(\alpha)$ and reallocate $(T_0)$

\[
\int_0^{+\infty} \exp(-\rho t) \frac{u'(c_{0,t}^N)}{u'(c_{0,0}^N)} \Delta_t^* dt = -\Phi^* (\alpha^{SB}, T_{0}^{SB}; \eta)
\]

\[
\int_{T_{0}^{SB}}^{+\infty} \exp(-\rho t) \frac{u'(c_{0,t}^A)}{u'(c_{0,0}^A)} \Delta_t dt = -\Phi (\alpha^{SB}, T_{0}^{SB}; \eta)
\]

\text{Proposition. (Constrained inefficiency)}

Fix weights $\eta$. Then, there is always a small perturbation of the technology $G^*(\cdot)$ such that either $\Phi^*(\cdot) \neq 0$ or $\Phi(\cdot) \neq 0$ — i.e., the equilibrium is generically constrained inefficient.
Taxing automation on efficiency grounds

- **No pref. for redistribution**: weights $\eta^\text{effic}$ so that distributional terms cancel out

  Government does not distort an efficient alloc. to improve redistribution
Taxing automation on efficiency grounds

- **No pref. for redistribution:** weights $\eta^{\text{effic}}$ so that distributional terms cancel out
  
  Government does not distort an efficient alloc. to improve redistribution

\[
\int_0^{+\infty} e^{-\rho t} \sum_h \phi^h \eta^h \cdot u'(c_{0,t}^h) \Delta_t^* dt = 0
\]

\[
\int_0^{+\infty} e^{-\rho t} \frac{u'(c_{0,0}^h)}{u'(c_{0,0}^N)} \Delta_t^* dt = 0
\]
Taxing automation on efficiency grounds

- **No pref. for redistribution**: weights $\eta^{\text{effic}}$ so that distributional terms cancel out.
  
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\[
\int_{0}^{+\infty} e^{-\rho t} \sum_{h} \phi_{h}^{h} \eta_{h,\text{effic}} \frac{u'(c_{0,t}^{h})}{u'(c_{0,0}^{h})} \Delta_{t}^{*} dt = 0
\]

\[
\int_{0}^{+\infty} e^{-\rho t} \frac{u'(c_{0,t}^{N})}{u'(c_{0,0}^{N})} \Delta_{t}^{*} dt = 0
\]

1. The response of output to automation $\Delta_{t}^{*}$ is **back-loaded**.

**Figure**
Taxing automation on efficiency grounds

- **No pref. for redistribution**: weights $\eta^{\text{effic}}$ so that distributional terms cancel out.
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\[
\int_0^{+\infty} e^{-\rho t} \sum_h \phi^h \eta^{h,\text{effic}} \frac{u'(c^h_{0,t})}{u'(c^h_{0,0})} \Delta^*_t \, dt = 0
\]

\[
\int_0^{+\infty} e^{-\rho t} \frac{u'(c^N_{0,t})}{u'(c^N_{0,0})} \Delta^*_t \, dt = 0
\]

1. The response of output to automation $\Delta^*_t$ is **back-loaded**.
2. Government is **more impatient** than the firm — priced by unconstrained workers only.
Taxing automation on efficiency grounds

▶ **No pref. for redistribution**: weights $\eta^\text{effic}$ so that distributional terms cancel out

Government does not distort an efficient alloc. to improve redistribution

(second best)  
$$\int_0^{+\infty} e^{-\rho t} \sum_h \phi^h \eta^h,\text{effic} \frac{u'(c^h_{0,t})}{u'(c^h_{0,0})} \Delta^*_t dt = 0$$

(laissez-faire)  
$$\int_0^{+\infty} e^{-\rho t} \frac{u'(c^{N,t}_{0})}{u'(c^{N,0}_{0})} \Delta^*_t dt = 0$$

1. The response of output to automation $\Delta_t^*$ is **back-loaded**

2. **Government** is *more impatient* than the firm — priced by unconstrained workers only

   $\rightarrow$ Optimal to **tax automation** on efficiency grounds
Taxing automation on efficiency grounds

- **No pref. for redistribution**: weights $\eta^\text{effic}$ so that distributional terms cancel out
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\int_0^{+\infty} e^{-\rho t} \sum_h \phi^h \eta^h,\text{effic} \frac{u'(c^h_0,t)}{u'(c^h_0,0)} \Delta_t^* dt = 0
\]

\[
\int_0^{+\infty} e^{-\rho t} \frac{u'(c^N_0,t)}{u'(c^N_0,0)} \Delta_t^* dt = 0
\]

The optimal **tax on automation** improves aggregate efficiency. It raises consumption early on in the transition, precisely when displaced workers value it more.
Extension: Gradual automation

- Tax capital in the long-run $\rightarrow$ improve **insurance** or prevent **dynamic inefficiency**
  
  (Aiyagari, 1995; Chamley, 2001; Conesa et al., 2009; Dávila et al., 2021; Aguiar et al.; 2021)
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- To clarify 2., extend model so that automation takes place **gradually**

\[
d\alpha_t = (x_t - \delta \alpha_t) \, dt;
\]

- Law of motion

\[
Y_t = G^* (\mu_t; \alpha_t) - x_t \alpha_t - \Omega (x_t / \alpha_t) \alpha_t
\]

- Output net of investment costs

Workers are unconstrained in the long-run ⇒ \( \alpha_{LF_t} / \alpha_{FB_t} \rightarrow 1 \) as \( t \rightarrow +\infty \)
Extension: Gradual automation

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\[ d\alpha_t = (x_t - \delta \alpha_t) \, dt; \]

\[ Y_t = G^* (\mu_t; \alpha_t) - x_t \alpha_t - \Omega (x_t/\alpha_t) \alpha_t \]

\[ \text{Law of motion} \quad \text{Output net of investment costs} \]

- Workers are unconstrained in the long-run \( \Rightarrow \alpha_t^{LF} / \alpha_t^{FB} \to 1 \) as \( t \to +\infty \)
Extension: Gradual automation

- Tax capital in the long-run → improve **insurance** or prevent **dynamic inefficiency**
  (Aiyagari, 1995; Chamley, 2001; Conesa et al., 2009; Dávila et al., 2021; Aguiar et al.; 2021)

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  \[
  d\alpha_t = (x_t - \delta \alpha_t) \, dt; \quad \text{Law of motion}
  \]

  \[
  Y_t = G^* (\mu_t; \alpha_t) - x_t \alpha_t - \Omega \left( x_t / \alpha_t \right) \alpha_t \quad \text{Output net of investment costs}
  \]

- **Workers are unconstrained** in the long-run \( \Rightarrow \alpha_t^{\text{LF}} / \alpha_t^{\text{FB}} \rightarrow 1 \) as \( t \rightarrow +\infty \)
Outline

Environment

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
Quantitative Model

Firm

task-based framework – Acemoglu-Autor

\[ y^h_t = F(\mu^h_t, \alpha^h_t) = A^h (\varphi^h \alpha^h_t + \mu^h_t)^{1-\eta} \]

quadratic adjustment costs – \( \omega \left( \frac{x_t}{\alpha_t} \right)^2 \alpha_t \)

\[ d\alpha^A_t = \left( x_t - \delta \alpha^A_t \right) dt \quad \alpha^N_t = 0 \]
Quantitative Model

Firm

task-based framework – Acemoglu-Autor

\[ y_t^h = F(\mu_t^h, \alpha_t^h) = A^h (\varphi^h \alpha_t^h + \mu_t^h)^{1-\eta} \]

quadratic adjustment costs \(-\omega (x_t/\alpha_t)^2 \alpha_t\)

\[ d\alpha_t^A = (x_t - \delta\alpha_t^A) \, dt \quad \alpha_t^N = 0 \]

Workers

gross flows – Kambourov-Manovskii

\[ S_t(x) = \frac{(1 - \phi) \exp \left( \frac{V_t^N(x'(N;x))}{\gamma} \right)}{\sum_{h'} \phi^{h'} \exp \left( \frac{V_t^{h'}(x'(h';x))}{\gamma} \right)} \]

uninsured risk – Huggett-Aiyagari

\[ dz_t^T = -\rho_z z_t^T \, dt + \sigma_z dW_t \]

\[ z_t^P = (1 - \theta) z_{t-}^P \text{ when moving} \]
Quantitative Model

**Firm**

- task-based framework – Acemoglu-Autor
  \[
  y_t^h = F(\mu_t^h, \alpha_t^h) = A^h (\varphi^h \alpha_t^h + \mu_t^h)^{1-\eta}
  \]
- quadratic adjustment costs – \(\omega \left(\frac{x_t}{\alpha_t}\right)^2 \alpha_t\)
  \[
  d\alpha_t^A = \left(x_t - \delta\alpha_t^A\right) dt \quad \alpha_t^N = 0
  \]

**Workers**

- gross flows – Kambourov-Manovskii
  \[
  S_t(x) = \frac{(1 - \phi) \exp \left(\frac{V_N^x(N;x)}{\gamma}\right)}{\sum_{h'} \phi^{h'} \exp \left(\frac{V_{h'}^x(h';x)}{\gamma}\right)}
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- uninsured risk – Huggett-Aiyagari
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**Calibration**

- internal (7) and external (14)
Quantitative Model

**Firm**

- **task-based framework** – Acemoglu-Autor

\[ y^h_t = F(\mu^h_t, \alpha^h_t) = A^h (\varphi^h \alpha^h_t + \mu^h_t)^{1-\eta} \]

- **quadratic adjustment costs** \(- \omega (x_t/\alpha_t)^2 \alpha_t\)

\[ d\alpha^A_t = (x_t - \delta \alpha^A_t) \, dt \quad \alpha^N_t = 0 \]

**Calibration**

- **internal (7) and external (14)**

**Workers**

- **gross flows** – Kambourov-Manovskii

\[ S_t(x) = (1 - \phi) \exp \left( \frac{V^N_t(x'(N;x))}{\gamma} \right) \]

\[ \frac{\sum_{h'} \phi^{h'} \exp \left( \frac{V^{h'}_t(x'(h';x))}{\gamma} \right)}{\phi} \]

- **uninsured risk** – Huggett-Aiyagari

\[ dz^T_t = -\rho_z z^T_t \, dt + \sigma_z dW_t \]

\[ z^P_t = (1 - \theta) z^P_{t-} \text{ when moving} \]
Automation, Reallocation and Inequality

**Automation**

**Share of workers in \( h = A \)**

**Relative wages**

**Consumption (log)**
Objective: The government maximizes
\[ W(\eta) \equiv \int_{-\infty}^{+\infty} \int \eta_t(x) V_{t}^{\text{birth}}(x) \, d\pi_t(x) \, dt \]

Second best: Choose \( \{\tau^x_t\} \) on investment, rebated to firm owners.

Numerically: Iterate on \( \{\tau^x_t\} \) (parametrically) to find the second best.
Welfare Gains Form Slowing Down Automation

Table: Welfare Gains at Second Best Intervention

<table>
<thead>
<tr>
<th></th>
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Note: ‘Long unempl.’ and ‘High liquid.’ are alternative calibrations with $1/\kappa = 2$ and $-B/Y = 1.4$. ‘Transfers’ denotes $10k$ to automated workers. ‘Joint’ denotes optimal tax on automation and transfers.
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- Half-life of automation: 20 years at LF and 47 years at SB in our benchmark
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| Transfers                | 0.3%                 | 3.0%        |
| Joint                    | 3.9%                 | 8.7%        |

Note: ‘Long unempl.’ and ‘High liquid.’ are alternative calibrations with $1/\kappa = 2$ and $-B/Y = 1.4$. ‘Transfers’ denotes $10k to automated workers. ‘Joint’ denotes optimal tax on automation and transfers.

- Half-life of automation: 20 years at LF and 47 years at SB in our benchmark
Takeaways

▶ Two novel results in economies where automation displaces workers, and these workers face reallocation and borrowing frictions.
Two novel results in economies where automation displaced workers, and these workers face reallocation and borrowing frictions.

1. Automation is inefficient when frictions are sufficiently severe
   Firms fail to internalize that automated workers have a limited ability to smooth consumption.

2. Optimal to slow down automation while workers reallocate, but not tax it in the long-run
   Improve aggregate efficiency by raising consumption when displaced workers are constrained.
Takeaways

▶ Two novel results in economies where automation displaces workers, and these workers face reallocation and borrowing frictions

1. Automation is inefficient when frictions are sufficiently severe
   Firms fail to internalize that automated workers have a limited ability to smooth consumption

2. Optimal to slow down automation while workers reallocate, but not tax it in the long-run
   Improve aggregate efficiency by raising consumption when displaced workers are constrained

▶ Quantitatively: substantial efficiency and welfare gains from slowing down autom.
   Even when the government can implement generous transfers
Contributions to the Literature

**Taxation of automation.** Naito (1999), Guerreiro et al. (2017), Thuemmel (2018), Rebelo et al. (2018), Costinot-Werning (2020), Jaimovich et al. (2020); Acemoglu et al. (2020); Korinek-Stiglitz (2021)

★ Policy interventions on efficiency grounds


★ Normative analysis with incomplete markets


★ Focus on taxation of automation with labor reallocation frictions
Example. A task-based technology (Acemoglu-Restrepo, 2018):

\[
G(\mu^A, \mu^N; \alpha) = \exp \left( \int_0^\phi \log (\varphi \alpha + \mu^A) + \int_{1-\phi}^1 \log (\mu^N) \right) \\
= (\varphi \alpha + \mu^A)^\phi \mu^N^{1-\phi}
\]

 Automation and labor are perfect substitutes within occupations.

 They can still be complements across occupations.

Borrowing

Distortions at the laissez-faire

- Consumption (PE)
- Reallocation (PE)
- Tight constraint
- Slow reallocation

Distributional effects

- Stopping time with $a \to -\infty$
- Prod. inefficiency
- Constraint not binding
- Constraint slack for all $t > T_0$
- Constraint binds for some $t > T_0$

$T_0 = S_1 S'_{10}$
Assumption (complementarity). $\partial_{\alpha} G^*(\mu, 1 - \mu; \alpha)$ has increasing differences in $(\alpha, -\mu)$.
Active labor market interventions might not be available (Heckman et al., Card et al.)
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The government uses automation ($\alpha$) as a proxy for reallocation ($T_0$)

$$\int_0^{+\infty} e^{-\rho t} \sum_h \phi_t^h \eta_t^h \frac{u'(c_{0,t}^h)}{u'(c_{0,0}^h)} (\Delta_t^* + T_0' (\alpha^{SB}) \Delta_t) \, dt = 0$$

so that

Short unempl/retraining spells ($1/\kappa$ low) $\rightarrow$ tax $\alpha$ more

Long unempl/retraining spells ($1/\kappa$ high) $\rightarrow$ tax $\alpha$ less
Active labor market interventions might not be available (Heckman et al., Card et al.)

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$$\int_0^{+\infty} e^{-\rho t} \sum_h \phi^h \eta^h \frac{u'(c_{0,t}^h)}{u'(c_{0,0}^h)} (\Delta_t^* + T_0' (\alpha^{SB}) \Delta_t) \, dt = 0$$

so that

Short unempl/retraining spells ($1/\kappa$ low) $\rightarrow$ tax $\alpha$ more

Long unempl/retraining spells ($1/\kappa$ high) $\rightarrow$ tax $\alpha$ less

We play with the duration of these spells ($1/\kappa$) in our quantitative model.
Extension II: Equity concerns

\[ \text{MRS}^A = \text{MRS}^N \]

\[ \text{LF} = \text{SB}^{\text{effic}} \]

\[ \text{Automation} \downarrow \]

\[ \text{MUA} = \text{MU}_N \]

\[ \text{FB}^{\text{utilit}} \]
Competitive Equilibrium

- **Incomes:**
  \[ Y^*_t(x) = \Pi_t + (1 - \tau_t) \times \begin{cases} \xi \exp(z) w^h_t & \text{if } e = E \\ b\xi \exp(z) w^{-h}_t & \text{if } e = U \end{cases} \]

  where \( b \) is replacement rate during unemployment.

- **Assets:**
  Workers trade riskless bonds, and annuities (Blanchard-Yaari)

- **Fiscal policy:**
  Constant debt / GDP, adjusts distortionary tax \( \{\tau_t\} \)

- **Resource constraint:**
  \[ \int c_t(x) d\pi_t + x_t + \omega \left( \frac{x_t}{\alpha_t} \right)^2 \alpha_t = G^* \left( \left\{ \int 1_{\{h(x) = h\}} \xi d\pi_t \phi^h \right\} \right) + b \int 1_{\{e = U\}} \tilde{Y}(x) d\pi_t, \]
**Parameters:** External calibration (14) and internal calibration (7)

**Table 1: Internal Calibration**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Calibration</th>
<th>Target / Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>Discount rate</td>
<td>0.10</td>
<td>2% real interest rate</td>
</tr>
<tr>
<td>$A^A$, $A^N$</td>
<td>Productivities</td>
<td>0.94, 1.16</td>
<td>Initial output (1)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Adjustment cost</td>
<td>4</td>
<td>Routine empl. share 2015</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Fraction of automated occupations</td>
<td>0.55</td>
<td>Routine empl. share 1970</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Mobility hazard</td>
<td>0.312</td>
<td>Occupational mobility 1970</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Fréchet parameter</td>
<td>0.052</td>
<td>Elasticity of labor supply</td>
</tr>
</tbody>
</table>
### Table 2: External Calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Calibration</th>
<th>Target / Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>EIS (inverse)</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Death rate</td>
<td>1/50</td>
<td>Average working life of 50 years</td>
</tr>
<tr>
<td>$1 - \eta$</td>
<td>Initial labor share</td>
<td>0.64</td>
<td>1970 labor share (BLS)</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Depreciation rate</td>
<td>0.1</td>
<td>Graetz-Michaels (2018)</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Elasticity of substitution across occs.</td>
<td>0.75</td>
<td>Buera-Kaboski (2011)</td>
</tr>
<tr>
<td>$1/\kappa$</td>
<td>Average unemployment duration</td>
<td>1/3.2</td>
<td>Alvarez-Shimer (2011)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Productivity loss from relocation</td>
<td>0.18</td>
<td>Kambourov-Manovskii (2009)</td>
</tr>
<tr>
<td>$a$</td>
<td>Borrowing limit</td>
<td>0</td>
<td>Auclert et al (2018)</td>
</tr>
<tr>
<td>$\phi_0, \phi_1, -B/Y$</td>
<td>Government</td>
<td>0.35, 0.18, 0.26</td>
<td>Heathcote et al (2017), Kaplan et al (2018)</td>
</tr>
<tr>
<td>$\rho_z, \sigma_z, b$</td>
<td>Income</td>
<td>0.023, 0.102, 0.4</td>
<td>Floden-Lindé (2001), Shimer (2005)</td>
</tr>
</tbody>
</table>