INEFFICIENT AUTOMATION

Martin Beraja (MIT)       Nathan Zorzi (Dartmouth)

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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)
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- 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 that can justify taxing automation:

(i) **Reallocation frictionless/absent**
   - Tax automation
   - Guerreiro et al, 2017; Costinot-Werning, 2018

(ii) **Govt. has preference for redistribution**

(iii) **Automation/reallocation are efficient**
   - Tax capital
   - Diamond 1965; Dávila et al, 2012; Davila-Korinek, 2018

(iii) **Dynamic ineff. or pecuniary externalities in IM**
   - Worker displacement/reallocation absent
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**Tax automation**

Guerreiro et al, 2017; Costinot-Werning, 2018

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Take worker displacement seriously. How should a government respond to automation?
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1. Recognize that displaced workers face two important frictions:
   
   (i) **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

   (ii) **Imperfect credit markets**: workers have limited ability to borrow against future incomes
       Jappelli et al, 2010; Chetty, 2008
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Take worker displacement seriously. \textbf{How should a government respond to automation?}

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2. Incorporate frictions in a \textbf{model} with endog. automation and heterog. agents

3. \textbf{Theoretical results}:
   \begin{itemize}
   \item[(i)] Interaction between frictions gives rise to \textbf{inefficient automation}
   \item[(ii)] Optimal to \textbf{tax automation} when govt. lacks instruments to fully alleviate frictions
     (even with no preference for redistribution)
   \end{itemize}
Take worker displacement seriously. How should a government respond to automation?

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        (even with no preference for redistribution)

4. Quantitative: gross flows + idiosync. risk → **welfare gains** from slowing down autom.

- Policy interventions on efficiency grounds


- Normative analysis with incomplete markets


- Focus on taxation of automation with labor reallocation frictions
Outline

Environment

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
Continuous time $t \geq 0$
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Workers $x = \{s, h, \xi\}$ (age, occupation, prod.)
**Environment**

Continuous time $t \geq 0$

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### Environment

Continuous time $t \geq 0$

**Occupations**

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

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

**Workers**

$U_0 = E_0 Z \exp(-\rho t) c^{1-\sigma} t^{1-\sigma} dt$

Resource constraint

$$Z c^t (x) d \Lambda = G^* \mu_A, \mu_N; \alpha \phi_h \mu_h t = Z \{h (x) = h\} \xi d \pi_t$$
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$F^*(1; \alpha)$ ↓ in $\alpha$ (*less labor-intensive*)

$F^*(1; \alpha)$ concave in $\alpha$ (*automation cost*)

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**ENVIRONMENT**

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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)
### Environment

**Continuous time** \( t \geq 0 \)

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\( x = \{ s, h, \xi \} \) (age, occupation, prod.)
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\[
\begin{pmatrix} 
\mu_t^A \\
\mu_t^N
\end{pmatrix} = \begin{cases} 
1 & \text{in } t = 0 \\
\text{Reallocation afterwards}
\end{cases}
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**Workers**

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

$$\left( \mu^A_t, \mu^N_t \right) \begin{cases} = 1 & \text{in } t = 0 \\ \text{Reallocation} & \text{afterwards} \end{cases}$$

$$U_0 = \mathbb{E}_0 \left[ \int \exp(-\rho t) \frac{c^1_1-\sigma}{1-\sigma} dt \right]$$
Environment

Continuous time \( t \geq 0 \)

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  \text{Reallocation afterwards} 
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\[
U_0 = E_0 \left[ \int \exp (-\rho t) \frac{c^1_{t}^1 - \sigma}{1 - \sigma} dt \right]
\]

Resource constraint

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

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

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

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
**First Best Problem**

Ex post problem

Ex ante problem
**First Best Problem**

**Ex post problem**

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

**Ex ante problem**
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

\[
\Delta_t \equiv (1 - \theta) \left( 1 - e^{-\kappa (t - T_{FB}^0)} \right) \left[ Y_t^N - Y_t^A \right]
\]

is the IRF of $Y$ to reallocation

Ex ante problem

Choose degree of automation $\alpha$

Reduce $C$ today, expand $Y$ tomorrow
(No OLG case)
**First Best Problem**

**Ex post problem**

- Reallocate labor and distribute output
- Close MPLs gap. Stop reallocation at $T_{FB}^0$
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$$\int_{T_{FB}^0}^{+\infty} e^{-\rho t} u' \left( c_t^N \right) \Delta_t dt = 0$$

**Ex ante problem**

Short unemployment or retraining

$$\sim (1 - \theta) Y_t^N - Y_t^A$$
**First Best Problem**

### Ex post problem

- Reallocate labor and distribute output
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(No OLG case)

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

### Ex ante problem

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

Ex post problem

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

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

Short unemployment or retraining
\[\sim (1 - \theta) (Y_N^t - Y_t^A)\]

Long unemployment or retraining

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)
**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^N \right) \Delta_t dt = 0
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**Ex ante problem**
- Choose degree of automation $\alpha^{FB}$
- Reduce $C$ today, expand $Y$ tomorrow

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\int_0^{+\infty} e^{-\rho t} u' \left( c_t^A \right) \Delta_t^* dt = 0
$$
Outline

Environment

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
Decentralized Choices

Firms

Workers

Assets: bonds, incomplete markets

Workers not insured against automation risk

\[ x = \{ a, s, h, \xi \} \]

\[ \text{da}_t(x) = \left[ Y^\star_t(x) + (r_t + \chi) a_t(x) - c_t(x) \right] dt \]

\[ a_t(x) \geq a \text{ for some } a \leq 0 \]

Definition of Equilibrium
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

Workers choose consumption $c$ and labor supply $\mu_t$.

Assets: bonds, incomplete markets.

Workers not insured against automation risk.

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

$$da_t(x) = \left[ Y^\star t(x) + (r_t + \chi) a_t(x) - c_t(x) \right] dt$$

$$a_t(x) \geq a$$ for some $a \leq 0$

Definition of Equilibrium
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Workers
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**Workers**

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**Assets:** bonds, incomplete markets

Workers not insured against automation risk
Decentralized Choices

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Choose automation $\alpha + \text{ labor demand } \mu_t$

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

Workers

Choose consumption $c$ and labor supply $\mu_t$

Assets: bonds, incomplete markets

Workers not insured against automation risk

$$x = \{a, s, h, \xi\} \ (\text{bonds, age, occ., prod.})$$
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 consumption $c$ and labor supply $\mu_t$

Assets: bonds, incomplete markets

Workers not insured against automation risk

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

$$da_t(x) = [\gamma_t^*(x) + (r_t + \chi)a_t(x) - c_t(x)] \, dt$$
**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**
Choose consumption $c$ and labor supply $\mu_t$

**Assets:** bonds, incomplete markets

Workers not insured against automation risk

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

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

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

Firms

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

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

$Q_t$: equity priced by unconst. workers

Workers

Choose consumption $c$ and labor supply $\mu_t$

Assets: bonds, incomplete markets

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

Efficient Allocation

Decentralized Equilibrium

**Failure of First Welfare Theorem**

Optimal Policy

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 \((1/\lambda or 1/\kappa > 0)\).
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 \((1/\lambda \text{ or } 1/\kappa > 0)\).

- **Interaction** between reallocation and borrowing frictions is key
- **Efficient cases:** instant realloc. (Costinot-Werning) or no borrowing frictions (Guerreiro et al)
Nature of the Inefficiency

Distortions at the laissez-faire

\[ a \leftrightarrow \hat{a}(\lambda) \]

\[ a^{\ast}(\lambda) \]

Consumption (PE)

Reallocation (PE)

Tight constraint

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

- **Automation.** Compare the optimality conditions

  (first best)

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

  (laissez-faire)

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

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

- **Automation.** Compare the optimality conditions
  (first best)               (laissez-faire)

\[
\int_{0}^{+\infty} e^{-\rho t} \frac{u'(A_0,t)}{u'(A_0,0)} \Delta^*_t dt = 0 \quad \int_{0}^{+\infty} e^{-\rho t} \frac{u'(N_0,t)}{u'(N_0,0)} \Delta^*_t dt = 0
\]

- **Automation**  \[ u'(A_{0,t}) > u'(N_{0,t}) \] → Rationale for redistribution
Why Is Automation Inefficient?

- **Automation.** Compare the optimality conditions

  (first best)

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

  (laissez-faire)

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

- **Automation** \[ u'(c_{0,t}^A) > u'(c_{0,t}^N) \] → Rationale for redistribution

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

- **Automation.** Compare the optimality conditions

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

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

- Automation \[ u'(c_{A,0},t) > u'(c_{N,0,t}) \] → Rationale for redistribution

- Borrowing constraints \[ \frac{u'(c_{A,0,t})}{u'(c_{A,0,0})} < \frac{u'(c_{N,t})}{u'(c_{N,0,0})} \] → Laissez-faire ≠ First best
Why Is Automation Inefficient?

- **Automation.** Compare the optimality conditions

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

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

- Automation \(\rightarrow\) \(u'(c^A_{0,t}) > u'(c^N_{0,t})\) \(\rightarrow\) Rationale for redistribution

- Borrowing constraints \(\rightarrow\) \(\frac{u'(c^A_{0,t})}{u'(c^A_{0,0})} < \frac{u'(c^N_{0,t})}{u'(c^N_{0,0})}\) \(\rightarrow\) Laissez-faire \(\neq\) First best

Firms are **too patient.** Partly overlook that benefits of automation take time to realize.
Environment

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
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

► When can we implement a first best with $\tau^\alpha = 0$?
How should a government respond to automation? Depends on the tools available

- Suppose: tax on automation $\tau^\alpha +$ arbitrary transfers/taxes to redistribute
- When can we implement a first best with $\tau^\alpha = 0$?
- Wedge between first best and laissez-faire optimality condition

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

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

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$$\tau^\alpha = \int_0^{+\infty} e^{-\rho t} \left( \frac{u'(c_{N0,t})}{u'(c_{N0,0})} - \frac{u'(c_{A0,t})}{u'(c_{A0,0})} \right) \Delta^*_t dt$$

Tools to redistribute income → alleviate borrowing cons. and close MRS gap
How should a government respond to automation? Depends on the tools available

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

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

   Informational requirements? (Piketty-Saez, 2013; Guerreiro et al., 2017; Costinot-Werning, 2018)
How should a government respond to automation? Depends on the tools available

- Suppose: tax on automation $\tau^\alpha +$ arbitrary transfers/taxes to redistribute
- When can we implement a first best with $\tau^\alpha = 0$?
- Wedge between first best and laissez-faire optimality condition

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

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

Fiscal cost? Govt. debt limits? (Araujo-Woodford, 2015; Daruich-Fernandez, 2020; Guner et al., 2021)
How should a government respond to automation? Depends on the tools available

- Suppose: **tax on automation** $\tau^\alpha + \text{arbitrary transfers/taxes to redistribute}

- When can we implement a first best with $\tau^\alpha = 0$?

- Wedge between first best and laissez-faire optimality condition

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

3. **Non-linear income taxes or unemp. insurance** → help but do not restore efficiency

Heterogeneity within occupations swamps heterogeneity between occupations (as in quant model)
Second best tools: tax automation (ex ante) + labor market interventions (ex-post)

Taxes/subsidies that depend on time, not worker-types. No social insurance for now.
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)*
  Taxes/subsidies that depend on time, not worker-types. No social insurance for now.

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

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

\[
\max_{\{\alpha, T_0, \mu_t, c_t\}} \sum_k \phi_k \eta_k \int_0^{+\infty} \exp(-\rho t) u\left(c_t^h\right) dt
\]

subject to workers’ budget constraints, the law of motion of labor, firms choosing labor optimally, and market clearing.
Government’s optimality conditions to automate ($\alpha$) and reallocate ($T_0$)

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

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

\{\text{laissez-faire}\} \quad \{\text{pecuniary externalities}\}
Government’s optimality conditions to **automate** ($\alpha$) and **reallocate** ($T_0$)

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

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

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

Guarantees that the government would not distort an efficient allocation for redistributive reasons
No pref. for redistribution: weights $\eta_{\text{effic}}$ so that distributional terms cancel out

Guarantees that the government would not distort an efficient allocation for redistributive reasons

(second best)

(laissez-faire)
Taxing automation on efficiency grounds

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

  Guarantees that the government would not distort an efficient allocation for redistributive reasons

(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)

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

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

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

Guarantees that the government would not distort an efficient allocation for redistributive reasons

(second best)  \hspace{2cm} (laissez-faire)

$$\int_0^{+\infty} e^{-\rho t} \sum_h \phi_h \eta^{h,\text{effic}} \frac{u'(c^{h}_0,t)}{u'(c^{h}_0,0)} \Delta^*_t dt = 0$$

$$\int_0^{+\infty} e^{-\rho t} \frac{u'(c^{N}_0,t)}{u'(c^{N}_0,0)} \Delta^*_t dt = 0$$

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
  Guarantees that the government would not distort an efficient allocation for redistributive reasons

(second best)  
(laissez-faire)

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

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

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

  $\rightarrow$ Optimal to **tax automation** on efficiency grounds
No pref. for redistribution: weights $\eta_{\text{effic}}$ so that distributional terms cancel out

Guarantees that the government would not distort an efficient allocation for redistributive reasons (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)

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

Taxing automation prevents excessive investment and raises consumption early on in the transition, precisely when displaced workers are borrowing-constrained
Active labor market interventions might not be available (Heckman et al., Card et al.)
Active labor market interventions might not be available (Heckman et al., Card et al.)

The government uses automation ($\alpha$) as a proxy for reallocation ($T_0$)

$$\int_0^{+\infty} e^{-\rho t} \sum_h \phi^h \eta^h \frac{u'(c^h_{0,t})}{u'(c^h_{0,0})} (\Delta^*_t + T'_0 (\alpha^{SB}) \Delta_t) \, dt = 0$$

so that

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

Long unempl/retraining spells ($1/\kappa$ high) $\rightarrow$ tax $\alpha$ less
Extension II: Equity Concerns

MRS^A = MRS^N

Efficiency

Automation ↓

SB^{effic}

Automation ↓

Equity

FB^{utilit}

MU^A = MU^N
Extension III: 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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- Rationale for taxing automation is distinct
  1. Does not rely on uninsured income risk
  2. Tax only during the transition, but not in the long-run once labor reallocation is complete
Tax capital in the long-run → Improve insurance or prevent dynamic inefficiency
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1. Does not rely on uninsured income risk

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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
Extension III: Gradual Automation

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\[ \frac{d\alpha_t}{dt} = (x_t - \delta\alpha_t) \]  
Law of motion

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

- Workers are unconstrained in the long-run \( \implies \alpha_t^{LF}/\alpha_t^{FB} \to 1 \) as \( t \to +\infty \)
Environment

Efficient Allocation

Decentralized Equilibrium

Failure of First Welfare Theorem

Optimal Policy

Quantitative Analysis
Quantitative Model

Firm

task-based framework – Acemoglu-Autor

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

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

\[ d\alpha^A_t = \left( x_t - \delta\alpha^A_t \right) dt \]

\[ \alpha^N_t = 0 \]
Quantitative Model

Firm

task-based framework – Acemoglu-Autor

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

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

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

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

**Firm**

task-based framework – Acemoglu-Autor

\[ y_t^h = F\left(\mu_t^h; \alpha_t^h\right) = A^h \left(\alpha_t^h + \mu_t^h\right)^{1-\eta} \]

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

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

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

uninsured risk – Huggett-Aiyagari

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

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

Calibration

internal (7) and external (13)
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: Vary the speed of automation \( \varphi \)

\[ \alpha_t = \alpha_0 + (1 - e^{-\varphi t}) (\alpha^{\text{CE}} - \alpha_0) \]

Implementation: \( \{\tau^x_t\} \) on investment, rebated to firm owners
### Table 1: Welfare Gains

<table>
<thead>
<tr>
<th>Half-life (years)</th>
<th>40</th>
<th>70</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W(\eta_{\text{effic}}; r_t) )</td>
<td>0%</td>
<td>2.3%</td>
<td>3.2%</td>
</tr>
<tr>
<td>( W(\eta_{\text{utilit}}; r_t) )</td>
<td>0%</td>
<td>2.8%</td>
<td>3.9%</td>
</tr>
</tbody>
</table>

- Within generations: utilitarian or efficient \( 1/V_t(\cdot) \) weights
- Across generations: discount with \( r_t \)
Takeaways

- Workers displaced by automation would like to borrow as they reallocate slowly
Takeaways

▶ Workers **displaced** by automation would like to borrow as they **reallocate slowly**

▶ **Borrowing constraints** create wedge between **interest rate** and **MRS** of workers
Takeaways

▶ Workers displaced by automation would like to borrow as they reallocate slowly

▶ Borrowing constraints create wedge between interest rate and MRS of workers

▶ Firms are effectively too patient when investing in automation
Workers *displaced* by automation would like to borrow as they *reallocate slowly*.

Borrowing constraints create wedge between *interest rate* and *MRS* of workers.

Firms are effectively *too patient* when investing in automation.

The government should *slow down* automation on *efficiency* grounds, even when it has no preference for redistribution.
Competitive equilibrium. Set of

1. Allocation for consumption \( \{c_t\} \) and labor supplies \( \{\mu_t, \Theta_t\} \), and automation \( \alpha \)
2. Interest rate \( \{r_t\} \), wages \( \{w_t^A, w_t^N\} \) and profits \( \{\Pi_t\} \)

such that

1. Workers consume, save and move optimally given prices
2. Representative firm chooses automation and hires labor optimally given prices
3. Labor markets clear and resource constraint holds
**Borrowing**

*Distortions at the laissez-faire*

![Diagram showing consumption (PE) and reallocation (PE) with parameters $\lambda$ and $\hat{a}(\lambda)$ and $a^*(\lambda)$, illustrating tight constraint and slow reallocation.]

*Distributional effects*

![Diagram illustrating distributional effects with stopping time $a_t^A$, constraint binds for some $t > T_0$, constraint slack for all $t > T_0$, and prod. inefficiency.]

- Constraint binds for some $t > T_0$.
- Constraint slack for all $t > T_0$.
- Prod. inefficiency.
- Constraint not binding.

**Distributional effects**

- Stopping time with $a \to -\infty$.

**Note:** The diagrams depict various economic concepts and parameters related to distortions and distributional effects under different conditions. The text accompanying the diagrams provides a narrative on how these concepts interrelate.
Response of output to automation

Output gains \((\alpha, -\mu)\) are complements

Crowding out
**Competitive Equilibrium**

- **Incomes:**
  \[
  \mathcal{Y}_t^* (x) = \Pi_t + (1 - \tau_t) \times \begin{cases} 
  \xi \exp (Z) w_t^h & \text{if } e = E \\
  b\xi \exp (Z) w_t^{-h} & \text{if } e = U 
  \end{cases}
  \]
  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:**
  \[
  \int c_t (x) d\pi_t + x_t + \omega \left( \frac{x_t}{\alpha_t} \right)^2 \alpha_t = G^* \left( \left\{ \int 1_{\{h(x) = h\}} \xi d\pi_t \right\} \right) + b \int 1_{\{e = U\}} \tilde{Y} (x) d\pi_t,
  \]
## Calibration

### 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>1/45</td>
<td>Average working life of 45 years</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Initial labor share</td>
<td>0.36</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>$1 - \kappa^*$</td>
<td>Probability of return move</td>
<td>0.44</td>
<td>Carillo-Tudela-Visschers (2020)</td>
</tr>
<tr>
<td>$1 - \theta$</td>
<td>Productivity loss from relocation</td>
<td>0.18</td>
<td>Kambourov-Manovskii (2009)</td>
</tr>
</tbody>
</table>
Parameters: External calibration (13) and internal calibration (7)
Parameters: External calibration (13) and internal calibration (7)

Table 3: 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>0.13</td>
<td>2% real interest rate</td>
</tr>
<tr>
<td>$A^A, A^N$</td>
<td>Productivities</td>
<td>0.89, 1.26</td>
<td>Initial output (1)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Adjustment cost</td>
<td>16</td>
<td>Routine empl. share 2015</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Fraction of automated occupations</td>
<td>0.53</td>
<td>Routine empl. share 1970</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Mobility hazard</td>
<td>0.49</td>
<td>Occupational mobility 1970</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Fréchet parameter</td>
<td>0.06</td>
<td>Elasticity of labor supply</td>
</tr>
</tbody>
</table>
### Table 4: External Calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Calibration</th>
<th>Target / Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Borrowing limit</td>
<td>0</td>
<td>Auclert et al. (2018)</td>
</tr>
<tr>
<td>(B/Y)</td>
<td>Government debt / GDP</td>
<td>0.26</td>
<td>Liquid assets / GDP</td>
</tr>
<tr>
<td>(\rho_z)</td>
<td>Mean reversion (inc)</td>
<td>0.9775</td>
<td>Floden-Linde (2001)</td>
</tr>
<tr>
<td>(\sigma_z)</td>
<td>Volatility (inc)</td>
<td>0.1025</td>
<td>Floden-Linde (2001)</td>
</tr>
<tr>
<td>(b)</td>
<td>Replacement rate while unemployed</td>
<td>0.4</td>
<td>Ganong et al. (2020)</td>
</tr>
</tbody>
</table>
Aggregate Allocations

Mass of workers in $h = A$

Profit share

No automation