INEFFICIENT AUTOMATION

Martin Beraja (MIT)       Nathan Zorzi (Dartmouth)

October 2023
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. Reallocation is frictionless or absent. Tax automation Guerreiro et al 2017; Costinot-Werning 2018

(i) Govt. has preference for redistribution

(ii) Automation/reallocation are efficient

Tax capital (long-run) Aiyagari 1995; Conesa et al. 2002

(i) Improve efficiency in economies with IM

(ii) Worker displacement/reallocation absent

- Take worker displacement seriously. How should we respond to automation?
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)
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
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. **Reallocation** is **frictionless** or **absent**

**Tax automation**

Guerreiro et al 2017; Costinot-Werning 2018

(i) Govt. has preference for redistribution

(ii) Automation/reallocation are efficient
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. **Reallocation is frictionless or absent**

**Tax automation**
Guerreiro et al 2017; Costinot-Werning 2018

(i) Govt. has preference for redistribution
(ii) Automation/reallocation are efficient

**Tax capital (long-run)**
Aiyagari 1995; Conesa et al. 2002

(i) Improve efficiency in economies with IM
(ii) Worker displacement/reallocation absent
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. **Reallocation is frictionless or absent**

**Tax automation**
Guerreiro et al 2017; Costinot-Werning 2018

**Tax capital (long-run)**
Aiyagari 1995; Conesa et al. 2002

Take worker displacement seriously. **How should we respond to automation?**
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; Landais-Spinnewijn, 2021
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; Landais-Spinnewijn, 2021

2. Incorporate frictions in a model with endog. automation and heterogeneous agents
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; Landais-Spinnewijn, 2021

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

3. **Theory (second best)**: gov’t can tax automation but lacks tools to alleviate frictions
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; Landais-Spinnewijn, 2021

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

3. **Theory (second best)**: gov’t can tax automation but lacks tools to alleviate frictions
   (i) Equilibrium is (generically) constrained inefficient and automation is **excessive**
       Firms do not internalize effect on workers’ incomes + Disagreement → Pareto improv’t
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; Landais-Spinnewijn, 2021

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

3. **Theory (second best)**: gov’t can tax automation but lacks tools to alleviate frictions
   
   (i) Equilibrium is (generically) constrained inefficient and automation is excessive
       Firms do not internalize effect on workers’ incomes + Disagreement → Pareto improv’t
   
   (ii) Optimal to **slow down automation** automation on efficiency grounds
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; Landais-Spinnewijn, 2021

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

3. Theory (second best): gov’t can tax automation but lacks tools to alleviate frictions
   (i) Equilibrium is (generically) constrained inefficient and automation is excessive
       Firms do not internalize effect on workers’ incomes + Disagreement → Pareto improv’t
   (ii) Optimal to **slown down automation** automation on efficiency grounds

4. Quantitative: gross flows + idiosync. risk → Optimal **speed** of automation + **welfare**
Environment

Laissez-Faire

Optimal Policy

Quantitative Analysis
Firms

Continuous time $t \geq 0$
Firms

Continuous time $t \geq 0$

Occupations
Continuous time $t \geq 0$

Occupations

$h = A$ (degree $\alpha \geq 0$) or $h = N$
Firms

Continuous time $t \geq 0$

Occupations

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

$y^A = F(\mu^A, \alpha), \quad y^N = F^*(\mu^N) \equiv F(\mu^N, 0)$
Continuous time $t \geq 0$

**Occupations**

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

\[ y^A = F(\mu^A, \alpha), \quad y^N = F^*(\mu^N) \equiv F(\mu^N, 0) \]

**Final good producer**

\[ G^* (\mu^A, \mu^N; \alpha) \equiv G \left( \left\{ y^h \right\} \right) - C(\alpha) \]
Continuous time $t \geq 0$

**Occupations**

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

$$y^A = F(\mu^A, \alpha), \quad y^N = F^*(\mu^N) \equiv F(\mu^N, 0)$$

**Final good producer**

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

**Automation**

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

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

Continuous time $t \geq 0$

Occupations

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

$y^A = F(\mu^A, \alpha)$, $y^N = F^*(\mu^N) \equiv F(\mu^N, 0)$

Final good producer

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

Automation

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

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

Profit maximization

$max_{\alpha \geq 0} \int_0^{+\infty} Q_t \Pi_t(\alpha) \, dt$
Firms

Continuous time $t \geq 0$

**Occupations**

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

$y^A = F(\mu^A, \alpha), \quad y^N = F^* (\mu^N) \equiv F(\mu^N, 0)$

**Final good producer**

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

**Automation**

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

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

**Profit maximization**

$max_{\alpha \geq 0} \int_0^{+\infty} Q_t \Pi_t (\alpha) \, dt$

$\Pi_t (\alpha) \equiv max_{\mu^A, \mu^N \geq 0} G^* (\mu^A, \mu^N; \alpha) - \mu^A \omega^A_t - \mu^N \omega^N_t$
Example based on Acemoglu-Restrepo (2018)
Example based on Acemoglu-Restrepo (2018)

Occupations $h = A$ or $h = N$. Technologies:

$$y^A = \varphi \alpha + \mu^A \quad \text{and} \quad y^N = \mu^N$$
Example based on Acemoglu-Restrepo (2018)

Occupations $h = A$ or $h = N$. Technologies:

$$y^A = \varphi \alpha + \mu^A \quad \text{and} \quad y^N = \mu^N$$

Aggregate production function:

$$G^* (\mu^A, \mu^N; \alpha) = \left[ (\varphi \alpha + \mu^A)^{\nu-1} \nu + (\mu^N)^{\nu-1} \nu \right]^{\frac{\nu}{\nu-1}} - \delta \alpha,$$
Example based on Acemoglu-Restrepo (2018)

Occupations $h = A$ or $h = N$. Technologies:

$$y^A = \varphi \alpha + \mu^A \quad \text{and} \quad y^N = \mu^N$$

Aggregate production function:

$$G^* (\mu^A, \mu^N; \alpha) = \left[ (\varphi \alpha + \mu^A)^{\frac{\nu-1}{\nu}} + (\mu^N)^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}} - \delta \alpha,$$

where $\delta$ is the marginal cost of automation.
Preferences

\[ U_0 = \int \exp(-\rho t) \frac{c_t^{1-\sigma}}{1-\sigma} dt \]
Preferences

\[ U_0 = \int \exp(-\rho t) \frac{c_t^{1-\sigma}}{1-\sigma} dt \]

Initial allocation

\[(\mu_t^A, \mu_t^N) \begin{cases} 
= 1/2 & \text{in } t = 0 \\
\text{Reallocation} & \text{afterwards}
\end{cases} \]
Workers

Preferences

\[ U_0 = \int \exp(-\rho t) \frac{c_t^{1-\sigma}}{1-\sigma} dt \]

Initial allocation

\[ \left( \mu_{t}^A, \mu_{t}^N \right) \begin{cases} 
= 1/2 & \text{in } t = 0 \\
\text{Reallocation} & \text{afterwards} 
\end{cases} \]

Budget constraint

\[ da_t^h = \left[ y_{t}^{h,*} + r_t a_t^h - c_t^h \right] dt \]
Preferences

\[ U_0 = \int \exp(-\rho t) \frac{c_t^{1-\sigma}}{1-\sigma} dt \]

Initial allocation

\[ (\mu_t^A, \mu_t^N) \begin{cases} 
  = 1/2 & \text{in } t = 0 \\
  \text{Reallocation afterwards} & \end{cases} \]

Budget constraint

\[ da_t^h = \left[ Y_t^{h,*} + r_t a_t^h - c_t^h \right] dt \]

Two frictions

1. Reallocation (neoclassical)

Random opportunities arrive at rate \( \lambda \)

Unempl. / retrain. exit at rate \( \kappa \)

Productivity loss \( \theta \)
Preferences

\[ U_0 = \int \exp(-\rho t) \frac{c_1^{1-\sigma}}{1-\sigma} dt \]

Initial allocation

\( (\mu_t^A, \mu_t^N) \)

\[
\begin{align*}
&= 1/2 \quad \text{in } t = 0 \\
&\text{Reallocation afterwards}
\end{align*}
\]

Budget constraint

\[ da_t^h = \left[ \gamma_t^{h,*} + r_t a_t^h - c_t^h \right] dt \]

Two frictions

1. Reallocation (neoclassical)
   - Random opportunities arrive at rate \( \lambda \)
Workers

Preferences

\[ U_0 = \int \exp(-\rho t) \frac{c_t^{1-\sigma}}{1-\sigma} dt \]

Initial allocation

\[ (\mu^A_t, \mu^N_t) \begin{cases} 
1/2 & \text{in } t = 0 \\
\text{Reallocation afterwards} & \text{Reallocation afterwards}
\end{cases} \]

Budget constraint

\[ da^h_t = \left[ Y^h_{t+} + r_t a^h_t - c^h_t \right] dt \]

Two frictions

1. Reallocation (neoclassical)
   - Random opportunities arrive at rate $\lambda$
   - Unempl. / retrain. exit at rate $\kappa$
Workers

Preferences

\[ U_0 = \int \exp(-\rho t) \frac{c_t^{1-\sigma}}{1-\sigma} dt \]

Initial allocation

\[ \left\{ \begin{array}{l}
\mu^A_t = 1/2 \\
\mu^N_t = 1/2
\end{array} \right. \quad \text{in } t = 0 \]

Reallocation afterwards

Budget constraint

\[ da^h_t = \left[ \mathcal{Y}^h_{t,*} + r_t a^h_t - c^h_t \right] dt \]

Two frictions

1. Reallocation (neoclassical)
   - Random opportunities arrive at rate \( \lambda \)
   - Unempl. / retrain. exit at rate \( \kappa \)
   - Productivity loss \( \theta \)
**Workers**

**Preferences**

\[ U_0 = \int \exp(-\rho t) \frac{c_t^{1-\sigma}}{1-\sigma} dt \]

**Initial allocation**

\[ \left\{ \begin{array}{l}
\mu^A_t, \mu^N_t \\
= 1/2 \quad \text{in } t = 0 \\
\text{Reallocation afterwards}
\end{array} \right. \]

**Budget constraint**

\[ da^h_t = \left[ h^*_t + r^h_t a^h_t - c^h_t \right] dt \]

**Two frictions**

1. **Reallocation** (neoclassical)
   - Random opportunities arrive at rate \( \lambda \)
   - Unempl. / retrain. exit at rate \( \kappa \)
   - Productivity loss \( \theta \)

2. **Borrowing**

\[ a^h_t \geq a \text{ for some } a \leq 0 \]
Resource constraint:

\[ \frac{1}{2} \sum_{h} c^h_t = G^* (\mu^A_t, \mu^N_t, \alpha) \]
Resource constraint:

\[
\frac{1}{2} \sum_h c_t^h = G^* (\mu_t^A, \mu_t^N; \alpha)
\]

Labor markets:

\[
w_t^h = G_n (\mu_t^A, \mu_t^N; \alpha) \quad \text{for each } h = A, N
\]
Resource constraint:

\[
\frac{1}{2} \sum_h c_t^h = G^*(\mu_t^A, \mu_t^N; \alpha)
\]

Labor markets:

\[
w_t^h = G_h(\mu_t^A, \mu_t^N; \alpha) \quad \text{for each } h = A, N
\]

No arbitrage:

\[
Q_t = \exp\left(- \int_0^t r_s ds\right)
\]
Resource constraint:
\[
\frac{1}{2} \sum_h c_t^h = G^* (\mu_t^A, \mu_t^N; \alpha)
\]

Labor markets:
\[
w_t^h = G_h (\mu_t^A, \mu_t^N; \alpha) \quad \text{for each } h = A, N
\]

No arbitrage:
\[
Q_t = \exp \left( - \int_0^t r_s ds \right)
\]

All agents act competitively.
Laissez-faire: Reallocation

- Wages $w_t^A < w_t^N$ due to automation
Laissez-faire: Reallocation

- Wages $w^A_t < w^N_t$ due to automation
- Reallocation from $h = A \rightarrow h = N$
Laissez-faire: Reallocation

- Wages $w_t^A < w_t^N$ due to automation
- Reallocation from $h = A \sim h = N$
- Stop reallocating at $T^{LF}$

$$\int_{T^{LF}}^{+\infty} e^{-\rho t} u'(c_t^A) \Delta_t dt = 0$$

where

$$\Delta_t \equiv (1 - \theta) \left( 1 - e^{-\kappa (t - T^{LF})} \right) \frac{w_t^N - w_t^A}{w_t^N - w_t^A}$$

denotes the output gains from reallocation
Laissez-faire: Binding borrowing constraints

Workers expect income to improve as they reallocate.
Workers expect income to improve as they reallocate → Motive for borrowing
Workers expect income to improve as they reallocate → Motive for borrowing
Laissez-faire: Binding borrowing constraints

Two benchmarks: instant realloc. (Costinot-Werning) or no borrowing frictions (Guerreiro et al)
Evidence: Earnings losses (Jacobson et al, Braxton-Taska) + Imperf. cons. smoothing (Landais-Spinnewijn)
Firm automation choice $\alpha_{LF}$: trades off cost $C(\alpha)$ with increase in output
Laissez-faire: Automation

- Firm automation choice $\alpha^{LF}$: trades off cost $C(\alpha)$ with increase in output

- Optimality condition

$$\int_{0}^{+\infty} Q_t \Delta^*_t \, dt = 0$$

where

$$\Delta^*_t \equiv \frac{\partial}{\partial \alpha} G^* (\mu^A_t, \mu^N_t; \alpha^{LF})$$

denotes the output gains (net of cost) from automation, and

$$Q_t = \exp \left( - \int_{0}^{t} r_s \, ds \right) = \exp (-\rho t) \frac{u' (c^N_t)}{u' (c^N_0)}$$

since non-automated workers are unconstrained (savers).
Environment

Laissez-Faire

Optimal Policy

Quantitative Analysis
How should a government respond to automation?

Primal problem: The government maximizes the social welfare function

\[ U = \frac{X}{\eta} + \int_{0}^{\infty} \exp(-\rho t) u_c(t) dt \]

by choosing \( \alpha, T, \mu_A, \mu_N, c_A(t), c_N(t) \) subject to workers choosing consumption optimally, the law of motion of labor, firms choosing labor optimally, and market clearing.
Constrained Ramsey problem

How should a government respond to automation?

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

- Depends on the **tools** available

- **First best tools**: lump sum transfers (directed, UBI)

  Info requirements? Fiscal cost? (Guerreiro et al., 2017; Costinot-Werning, 2018, Guner et al., 2021)
How should a government respond to automation?

- Depends on the **tools** available

- **Second best tools:** tax automation + active labor market interventions

  E.g., South Korea’s reduction in automation tax credit in manuf; Geneva’s tax on automated cashiers. Severance or higher payroll tax after layoffs from automation, as for other qualifying layoffs in the US?
How should a government respond to automation?

- Depends on the tools available

- **Second best tools**: tax automation + active labor market interventions
  
  E.g., South Korea’s reduction in automation tax credit in manuf; Geneva’s tax on automated cashiers.
  
  Severance or higher payroll tax after layoffs from automation, as for other qualifying layoffs in the US?

- **Primal problem**: The government maximizes the social welfare function

\[
U \equiv \sum_{h} \eta^{h} \int_{0}^{+\infty} \exp(-\rho t) u \left(c^{h}_{t}\right) dt
\]

by choosing \(\{\alpha, T, \mu^{A}_{t}, \mu^{N}_{t}, c^{A}_{t}, c^{N}_{t}\}\) subject to workers choosing consumption optimally, the law of motion of labor, firms choosing labor optimally, and market clearing.
Consider a perturbation $\delta \alpha$ starting from the laissez-faire. Welfare change

$$\frac{\delta U}{\delta \alpha} = \eta^N u' (c^N_0) \times \int_0^{+\infty} \exp (-\rho t) \frac{u' (c^N_t)}{u' (c^N_0)} \times \left( \hat{c}^N_t + \bar{c}^N_* \right) dt$$

$$+ \eta^A u' (c^A_0) \times \int_0^{+\infty} \exp (-\rho t) \frac{u' (c^A_t)}{u' (c^A_0)} \times \left( \hat{c}^A_t + \bar{c}^A_* \right) dt$$

where $\hat{c}^h_* = \text{time-varying terms (zero PDV)}$ and $\bar{c}^A_* + \bar{c}^N_* = 0$ are distributional.
Aggregate vs. Distributional Effects

Consider a perturbation $\delta \alpha$ starting from the laissez-faire. Welfare change

$$\frac{\delta U}{\delta \alpha} = \eta^N u'(c^N_0) \times \int_0^{+\infty} \exp(-\rho t) \frac{u'(c^N_t)}{u'(c^N_0)} \times \left( \tilde{c}_t^N + \tilde{c}_t^N,* \right) dt$$

$$= \exp\left(-\int_0^t \rho \text{d}s\right)$$

$$+ \eta^A u'(c^A_0) \times \int_0^{+\infty} \exp(-\rho t) \frac{u'(c^A_t)}{u'(c^A_0)} \times \left( \tilde{c}_t^A + \tilde{c}_t^A,* \right) dt$$

How automated workers value flows

where $\tilde{c}_t^h,*$ are time-varying terms (zero PDV) and $\tilde{c}_t^A,* + \tilde{c}_t^N,* = 0$ are distributional.

No borrowing constraints $\rightarrow \frac{u'(c^N_t)}{u'(c^N_0)} = \frac{u'(c^A_t)}{u'(c^A_0)} \rightarrow$ Efficiency (only distributional terms)
Consider a perturbation $\delta \alpha$ starting from the laissez-faire. Welfare change

$$\frac{\delta U}{\delta \alpha} = \eta^N u' \left( c^N_t \right) \times \int_0^{+\infty} \exp \left( -\rho t \right) \frac{u' \left( c^N_t \right)}{u' \left( c^N_0 \right)} \times \left( \hat{c}^N_t + \bar{c}^N_\ast \right) dt$$

$$+ \eta^A u' \left( c^A_0 \right) \times \int_0^{+\infty} \exp \left( -\rho t \right) \frac{u' \left( c^A_t \right)}{u' \left( c^A_0 \right)} \times \left( \hat{c}^A_t + \bar{c}^A_\ast \right) dt$$

How automated workers value flows

where $\hat{c}^h_\ast$ are time-varying terms (zero PDV) and $\bar{c}^A_\ast + \bar{c}^N_\ast = 0$ are distributional.

No borrowing constraints $\rightarrow \frac{u' \left( c^N_t \right)}{u' \left( c^N_0 \right)} = \frac{u' \left( c^A_t \right)}{u' \left( c^A_0 \right)} \rightarrow$ Efficiency (only distributional terms)

There is still an equity rationale since $u' \left( c^N_t \right) < u' \left( c^A_t \right)$, e.g., utilitarian weights.
Consider a perturbation $\delta\alpha$ starting from the laissez-faire. Welfare change

$$\frac{\delta U}{\delta\alpha} = \eta^N u'(c^N_0) \times \int_0^{+\infty} \exp\left(-\rho t\right) \frac{u'(c^N_t)}{u'(c^N_0)} \times \left(\hat{c}^{N,*}_t + \bar{c}^{N,*}\right) dt$$

$$+ \eta^A u'(c^A_0) \times \int_0^{+\infty} \exp\left(-\rho t\right) \frac{u'(c^A_t)}{u'(c^A_0)} \times \left(\hat{c}^{A,*}_t + \bar{c}^{A,*}\right) dt$$

How automated workers value flows

where $\hat{c}^{h,*}_t$ are time-varying terms (zero PDV) and $\bar{c}^{A,*} + \bar{c}^{N,*} = 0$ are distributional.

Borrowing constraints $\frac{u'(c^N_t)}{u'(c^N_0)} > \frac{u'(c^A_t)}{u'(c^A_0)} \rightarrow$ Inefficiency ($\delta U/\delta\alpha \neq 0$)
Consider a perturbation \( \delta \alpha \) starting from the laissez-faire. Welfare change

\[
\frac{\delta U}{\delta \alpha} = \eta^N u' (c^N_0) \times \int_0^{+\infty} \exp(-\rho t) \frac{u'(c_t^N)}{u'(c^N_0)} \times \left( \hat{c}_t^{N,*} + \bar{c}^{N,*} \right) dt
\]

\[
+ \eta^A u' (c^A_0) \times \int_0^{+\infty} \exp(-\rho t) \frac{u'(c_t^A)}{u'(c^A_0)} \times \left( \hat{c}_t^{A,*} + \bar{c}^{A,*} \right) dt
\]

How automated workers value flows

where \( \hat{c}_t^{h,*} \) are time-varying terms (zero PDV) and \( \bar{c}^{A,*} + \bar{c}^{N,*} = 0 \) are distributional.

Borrowing constraints \( \rightarrow \frac{u'(c_t^N)}{u'(c^N_0)} > \frac{u'(c_t^A)}{u'(c^A_0)} \rightarrow \text{Inefficiency } (\delta U/\delta \alpha \neq 0) \)

Firms do not fully internalize how automation affects incomes. Source of ineff. if firms (or \( N \) workers) and \( A \) workers disagree on how they value income over time.
**Proposition.** (Constrained inefficiency)

Generically, there exists \( \{\delta \alpha, \delta T\} \) such that \( \delta U^A > 0 \) and \( \delta U^N = 0 \). This requires \( \delta \alpha < 0 \).
Proposition. (Constrained inefficiency)

Generically, there exists \( \{\delta \alpha, \delta T\} \) such that \( \delta U^A > 0 \) and \( \delta U^N = 0 \). This requires \( \delta \alpha < 0 \).
Constrained Inefficiency (for any Pareto weights)

**Proposition.** (Constrained inefficiency)

Generically, there exists \( \{\delta \alpha, \delta T\} \) such that \( \delta U^A > 0 \) and \( \delta U^N = 0 \). This requires \( \delta \alpha < 0 \).

Taxing automation \( \delta \alpha < 0 \) benefits \( A \) but hurts \( N \) workers.
Proposition. (Constrained inefficiency)

Generically, there exists \( \{\delta \alpha, \delta T\} \) such that \( \delta U^A > 0 \) and \( \delta U^N = 0 \). This requires \( \delta \alpha < 0 \).

Can compensate \( N \) workers \( (\delta U^N = 0) \) with \( \delta T < 0 \).
Proposition. (Constrained inefficiency)

Generically, there exists \( \{\delta \alpha, \delta T\} \) such that \( \delta U^A > 0 \) and \( \delta U^N = 0 \). This requires \( \delta \alpha < 0 \).

A workers are hurt more by losses early on. Policy alleviates those \( (\delta U^A > 0) \)
Proposition. (Constrained inefficiency)

Generically, there exists \( \{\delta \alpha, \delta T\} \) such that \( \delta U^A > 0 \) and \( \delta U^N = 0 \). This requires \( \delta \alpha < 0 \).

Taxing automation raises income of displaced worker early on during the transition precisely when they value it more.
Optimal Policy Intervention

Optimal intervention depends on how the government values efficiency vs. equity.
Optimal Policy Intervention

- Optimal intervention depends on how the government values efficiency vs. equity.
- Optimality condition wrt $\alpha$

$$\frac{\partial U}{\partial \alpha} = \sum_h \eta^h \int_0^{+\infty} \exp(-\rho t) u\left(c^h_t\right) \times \hat{c}^h_t \, dt + \sum_h \eta^h \int_0^{+\infty} \exp(-\rho t) u\left(c^h_t\right) \, dt \times \bar{c}^h_t$$

Taxing $\alpha$ on efficiency grounds

Taxing $\alpha$ on equity grounds

Proposition. (Taxing automation on efficiency grounds)

A government using efficiency weights $\eta^h_{\text{effic}}$ finds it optimal to tax automation.

- Pref. for equity: Government taxes even more with utilitarian weights.

No pref. for equity: The government uses efficiency weights $\eta^h_{\text{effic}}$, and the government does not distort an efficient allocation to improve equity (think "inverse marginal utility weights").
Optimal Policy Intervention

- Optimal intervention depends on how the government values efficiency vs. equity.
- Optimality condition wrt $\alpha$

$$\partial_\alpha U = \sum_h \eta^{h, \text{effic}} \int_0^{+\infty} \exp(-\rho t) u'(c_t^h) \times \hat{c}_t^{h,*} \, dt + \sum_h \eta^h \int_0^{+\infty} \exp(-\rho t) u'(c_t^h) \, dt \times \bar{c}_t^{h,*}$$

- **No pref. for equity**: The government uses efficiency weights $\{\eta^{h, \text{effic}}\}$
  Gov’t does not distort an efficient allocation to improve equity (think “inverse marginal utility weights”)

- Taxing $\alpha$ on efficiency grounds
- Taxing $\alpha$ on equity grounds
Optimal Policy Intervention

- Optimal intervention depends on how the government values efficiency vs. equity.
- Optimality condition wrt $\alpha$

$$\partial_\alpha U = \sum_h \eta^{h,\text{effic}} \int_0^{+\infty} \exp(-\rho t) u'(c^h_t) \times \hat{c}^{h,*} \, dt + \sum_h \eta^h \int_0^{+\infty} \exp(-\rho t) u'(c^h_t) \, dt \times \bar{c}^{h,*}$$

- **No pref. for equity**: The government uses efficiency weights $\{\eta^{h,\text{effic}}\}$

  Gov't does not distort an efficient allocation to improve equity (think "inverse marginal utility weights")
Optimal Policy Intervention

- Optimal intervention depends on how the government values efficiency vs. equity.
- Optimality condition wrt $\alpha$

$$\frac{\partial U}{\partial \alpha} = \eta_{A,\text{effic}} \int_{0}^{+\infty} \exp(-\rho t) u'(c_t^A) \times \hat{c}_t^A,\star dt$$

Taxing $\alpha$ on efficiency grounds

- No pref. for equity: The government uses efficiency weights $\{\eta_{h,\text{effic}}\}$

Gov't does not distort an efficient allocation to improve equity (think "inverse marginal utility weights")
Optimal Policy Intervention

▶ Optimal intervention depends on how the government values efficiency vs. equity.
▶ Optimality condition wrt $\alpha$. **Negative when evaluated at laissez-faire**

$$\partial_\alpha U = \eta_{A,\text{effic}} \int_0^{+\infty} \left[ \exp(-\rho t) u'(c^A_t) \times \hat{c}^A_t,^* \right] \, dt < 0$$

$$<u'(c^A_0) \exp(-\int_0^t r_s \, ds) < 0 \text{ early on, } > 0 \text{ later}$$

▶ **No pref. for equity**: The government uses **efficiency weights** $\{\eta^{h,\text{effic}}\}$

Gov’t does not distort an efficient allocation to improve equity (think "inverse marginal utility weights")

**Proposition.** (Taxing automation on efficiency grounds)

A government using efficiency weights $\{\eta^{h,\text{effic}}\}$ finds it optimal to tax automation.
Optimal Policy Intervention

- Optimal intervention depends on how the government values efficiency vs. equity.
- Optimality condition wrt $\alpha$. **Negative when evaluated at laissez-faire**

\[
\partial_\alpha U = \eta^{A,\text{effic}} \int_0^{+\infty} \exp(-\rho t) u'(c^A_t) \times \hat{c}^{A,*}_t \, dt < 0
\]

- **No pref. for equity**: The government uses **efficiency weights** $\{\eta^{h,\text{effic}}\}$
  Gov’t does not distort an efficient allocation to improve equity (think “inverse marginal utility weights”)

**Proposition. (Taxing automation on efficiency grounds)**

A government using efficiency weights $\{\eta^{h,\text{effic}}\}$ finds it optimal to tax automation.

- **Pref. for equity**: Government taxes even more with utilitarian weights
Tax capital → might improve insurance or prevent capital overaccumulation (Aiyagari, 1995; Conesa et al., 2009; Dávila et al., 2021)
Extension: Gradual automation

- Tax capital → might improve insurance or prevent capital overaccumulation
  (Aiyagari, 1995; Conesa et al., 2009; Dávila et al., 2021)

- This paper: different rationale for taxing automation
Extension: Gradual automation

- Tax capital → might improve insurance or prevent capital overaccumulation
  (Aiyagari, 1995; Conesa et al., 2009; Dávila et al., 2021)

- This paper: different rationale for taxing automation
  
  1. Does not rely on uninsured income risk

  2. Slow down automation only while workers reallocate and are borrowing constrained. No tax in the long-run.
Tax capital → might improve **insurance** or prevent **capital overaccumulation**
(Aiyagari, 1995; Conesa et al., 2009; Dávila et al., 2021)

This paper: **different rationale** for taxing automation

1. Does not rely on **uninsured income risk**

2. **Slow down** automation only while **workers reallocate** and are borrowing constrained. **No** tax in the long-run.

To clarify 2., add important features over long horizons: **gradual automation + OLG**

\[
\begin{align*}
\frac{d\alpha_t}{dt} &= (x_t - \delta \alpha_t) \quad \text{Law of motion} \\
Y_t &= G^*(\mu_t; \alpha_t) - q_t x_t \quad \text{Output net of investment cost}
\end{align*}
\]
Extension: Gradual automation

- Tax capital → might improve insurance or prevent capital overaccumulation
  (Aiyagari, 1995; Conesa et al., 2009; Dávila et al., 2021)

- This paper: **different rationale** for taxing automation
  1. Does not rely on uninsured income risk
  2. **Slow down** automation only while workers reallocate and are borrowing constrained. No tax in the long-run.

- To clarify 2., add important features over long horizons: **gradual automation** + OLG

\[
d\alpha_t = (x_t - \delta \alpha_t) \, dt; \quad Y_t = G^* (\mu_t; \alpha_t) - q_t x_t
\]

- **Workers have identical MRS and MU** in the long-run \( \alpha_t^{\text{LF}} / \alpha_t^{\text{FB}} \to 1 \) as \( t \to +\infty \)

No efficiency nor equity rationale for intervention
Environment

Laissez-Faire

Optimal Policy

Quantitative Analysis
Quantitative Model

Firm

Production – Acemoglu-Restrepo

\[ y_t^A = A^A (\alpha + \mu^A)^{1-\eta} \quad \text{and} \quad y_t^N = A^N (\mu^N)^{1-\eta} \]

\[ Y = \left[ \phi \left( y_t^A \right)^{\frac{\nu-1}{\nu}} + (1 - \phi) \left( y_t^N \right)^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}} \]

Investment – Guerreiro et al

Law of motion: \( d\alpha_t = (x_t - \delta \alpha_t) \, dt \); \( \alpha_0 = 0 \)

Cost p/unit: \( q_t = q^{\text{fin}} + \exp (-\psi t) \left( q^{\text{init}} - q^{\text{fin}} \right) \)
### Quantitative Model

#### Firm

**Production – Acemoglu-Restrepo**

\[
y_t^A = A^A (\alpha + \mu^A)^{1-\eta} \quad \text{and} \quad y_t^N = A^N (\mu^N)^{1-\eta}
\]

\[
Y = \left[ \phi \left( y_t^A \right)^{\frac{\nu-1}{\nu}} + (1-\phi) \left( y_t^N \right)^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}}
\]

**Investment – Guerreiro et al**

Law of motion: \( d\alpha_t = (x_t - \delta \alpha_t) \, dt; \, \alpha_0 = 0 \)

Cost p/unit: \( q_t = q^{\text{fin}} + \exp(-\psi t) \left( q^{\text{init}} - q^{\text{fin}} \right) \)

#### Workers

**Gross flows – Kambourov-Manovskii**

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

**Uninsured risk – Huggett-Aiyagari**

\[
Y_t^{\text{labor}}(x) = \xi \exp(z) w_t^h
\]

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

\[
\xi_t = (1 - \theta) \xi_{t,-} \quad \text{if move; Replacement rate } b
\]

\[
Y_t^{\text{net}}(x) = T \left( Y_t^{\text{labor}}(x) + \exp(z) \Pi_t^{\text{div}} \right)
\]
Calibration

- Initial stationary eq (no automation) = year 1980. A occupations = Routine-intensive
- Mix of external (15 param.) and internal (8 param.) calibration

### 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>0.04</td>
<td>2% real interest rate</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Mobility hazard</td>
<td>0.364</td>
<td>Gross mobility 1980 (10%)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Fréchet parameter</td>
<td>0.036</td>
<td>Elasticity of labor supply (1)</td>
</tr>
<tr>
<td>$A^A, A^N$</td>
<td>Productivities</td>
<td>0.719, 1.710</td>
<td>$Y_0 = 1$, symm. wages</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Share of automated occupations</td>
<td>0.537</td>
<td>Routine empl. share 1980 (55%)</td>
</tr>
<tr>
<td>$q^{fin}$</td>
<td>Final cost of autom.</td>
<td>5.621</td>
<td>Log wage gap (0.45) in Cortes et al (2016)</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Cost convergence rate</td>
<td>0.054</td>
<td>Half-life of wage gap (15 yrs) in Cortes et al (2016)</td>
</tr>
</tbody>
</table>
Half-life of automation: 16 years at LF v. 22 years at SB
### Welfare Gains From Slowing Down Automation

<table>
<thead>
<tr>
<th></th>
<th>Benchmark</th>
<th>Less liquidity</th>
<th>Less reallocation</th>
<th>More complements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated</td>
<td>0.80%</td>
<td>0.91%</td>
<td>0.93%</td>
<td>0.78%</td>
</tr>
<tr>
<td>Non-autom.</td>
<td>−0.19%</td>
<td>−0.22%</td>
<td>−0.35%</td>
<td>−0.21%</td>
</tr>
<tr>
<td>New gener.</td>
<td>−0.08%</td>
<td>−0.11%</td>
<td>−0.10%</td>
<td>−0.08%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.20%</strong></td>
<td><strong>0.24%</strong></td>
<td><strong>0.20%</strong></td>
<td><strong>0.19%</strong></td>
</tr>
</tbody>
</table>

Note: ‘Less liquidity’ and ‘Less reallocation’ denote alternative calibrations where we target a ratio of liquidity to GDP of 0.35 (instead of 0.5) and a separation rate of 7.2% (instead of 10%), respectively. ‘More complements’ denotes an alternative calibration where the elasticity of substitution across occupations is 0.76 (instead of 0.9).
## Welfare Gains From Slowing Down Automation

<table>
<thead>
<tr>
<th></th>
<th>Benchmark</th>
<th>Less liquidity</th>
<th>Less reallocation</th>
<th>More complements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated</td>
<td>0.80%</td>
<td>0.91%</td>
<td>0.93%</td>
<td>0.78%</td>
</tr>
<tr>
<td>Non-autom.</td>
<td>−0.19%</td>
<td>−0.22%</td>
<td>−0.35%</td>
<td>−0.21%</td>
</tr>
<tr>
<td>New gener.</td>
<td>−0.08%</td>
<td>−0.11%</td>
<td>−0.10%</td>
<td>−0.08%</td>
</tr>
<tr>
<td>Total</td>
<td>0.20%</td>
<td>0.24%</td>
<td>0.20%</td>
<td>0.19%</td>
</tr>
</tbody>
</table>

Note: ‘Less liquidity’ and ‘Less reallocation’ denote alternative calibrations where we target a ratio of liquidity to GDP of 0.35 (instead of 0.5) and a separation rate of 7.2% (instead of 10%), respectively. ‘More complements’ denotes an alternative calibration where the elasticity of substitution across occupations is 0.76 (instead of 0.9).

**Wage supplements:** Second best is as if the gov’t gave $19,126 to each A worker, and taxed $4,622 each N worker in PDV. Total fiscal cost: 1.1 trn.
Two novel results in economies where automation displaces workers, and these workers face reallocation and borrowing frictions.
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 do not internalize effect on displaced workers who are borrowing constrained

2. Optimal to slow down automation while workers reallocate, but not tax it in the long-run
   Raise income of displaced workers when they value it more
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 do not internalize effect on displaced workers who are borrowing constrained

2. Optimal to slow down automation while workers reallocate, but not tax it in the long-run
   Raise income of displaced workers when they value it more

Quant: Meaningful efficiency and welfare gains from slowing down automation
ARE THE RATIONALES FOR SLOWING DOWN AI AS STRONG AS THEY WERE FOR ROBOTS?
AI (generative, LLMs) ≠ Robots

- **Equity** rationale seems much **weaker for AI** than it was for robots
  - Robots automate routine, low-to-middle-wage jobs (car manuf)
  - AI (likely) automates cognitive, middle-to-high-wage jobs (lawyers, journos, soft devs)

---

Eloundou et al (2023)

Acemoglu and Restrepo (2022)
Efficiency rationale seems much weaker too

- Lawyers, journos, and soft devs not the first that come to mind as "financially vulnerable"
- Call centers? College debt?

Eloundou et al (2023)

Acemoglu and Restrepo (2022)
AI (GENERATIVE, LLMs) ≠ ROBOTS

- **Efficiency** rationale seems much **weaker too**
  - Lawyers, journos, and soft devs not the first that come to mind as "financially vulnerable"
  - Call centers? College debt?

- Weaker rationale for slowing down AI due to job automation. AI **alignment** concerns?

Eloundou et al (2023)

Acemoglu and Restrepo (2022)
Active labor market interventions might not be available (Heckman et al., Card et al.)

- Gov’t now internalizes indirect effect of automation due to reallocation $T'(\alpha) > 0$

\[
T'(\alpha) \times \frac{1}{2} \lambda \exp(-\lambda T) \times \int_{T(\alpha)}^{+\infty} \exp(-\rho t) \left\{ \eta^N u'(c^N_t) - \eta^A u'(c^A_t) \right\} \times \partial_t c^N_t dt
\]

- Can reinforce or dampen incentives to tax automation, depending on Pareto weights.

- Utilitarian → tax less. Efficiency weights → tax more.