Steering Technological Progress

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Motivate

Motivation:

- since Industrial Revolution: technological progress has improved living standards 20x
- in recent decades: fruits of progress shared increasingly unevenly
- Artificial Intelligence threatens most (all?) labor with redundancy

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progress is not exogenous but (for now, at least) driven by human decisions

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Research Question

How should we steer technological progress while taking into account its distributive impact?

Premise

Assumptions:

- **Premise:** it is desirable for economy to offer well-paying jobs
  - either because large-scale redistribution is impossible, for incentive or political-economy reasons
  - or because paid work directly provides certain forms of utility

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- **Premise:** it is desirable for economy to offer well-paying jobs
  - either because large-scale redistribution is impossible, for incentive or political-economy reasons
  - or because paid work directly provides certain forms of utility
- **Direction of future technological progress is crucial:** for example,
  - Google Maps: has enabled millions to earn income as drivers
  - Google Waymo: threatens to put millions out of their jobs

Contribute

Existing Literature:

- **Endogenous/directed technical change**
- **Optimal taxation**

Setup

Baseline Setup:

- $i = 1, ...I$ agents with utility over a single consumption good $u^i\left(c^i\right)$
- $h = 1, ..., H$ factors of production
- factor endowments $\ell^i = (\ell^{i1}, ..., \ell^{iH})'$ add up to aggregate $\ell = \sum_i \ell^i$
- representative firm with CRS production function

$$y = F\left(\ell; A\right)$$

  where $A \in \mathcal{A} \subseteq \mathbb{R}^K$ is a vector of technological parameters
- social planner with weights $\left\{\theta^i\right\}$ on individual utilities where $\sum_i \theta^i = 1$

$$\max W = \sum_i \theta^i u^i\left(c^i\right)$$

- using $\left\{\theta^i\right\}$ to define a probability measure, we can re-express this as

$$W = E_i\left[u^i\left(c^i\right)\right]$$

First-Best

First Best:

- costless redistribution
- social planner

$$\max_{c^i, A} W = \sum_i \theta^i u^i \left(c^i\right) \quad \text{s.t.} \quad \sum_i c^i = F\left(\ell; A\right)$$

- FOC (assuming interior solution):

$$\theta^i u' \left(c^i\right) = \lambda \quad \forall i$$
$$\lambda F_{A^k}\left(\ell; A\right) = 0 \quad \forall k$$

$\rightarrow$ redistribution is not an issue, focus on production efficiency

Definition (Production Efficiency)

For given ℓ, denote the efficiency-maximizing technological parameters $A^*\left(\ell\right)$ and the associated level of output $y^*(\ell)$ so that

$$A^*\left(\ell\right) = \arg\max_A F\left(\ell; A\right) \quad \text{and} \quad y^*\left(\ell\right) = F\left(\ell; A^*\right)$$

Laisser Faire Equilibrium

Market Structure:

- consumers obtain income from factor rents $c^i = w \cdot \ell^i$
- assume each firm can pick technology parameter A

$$\max_{\ell,A} \Pi = F(\ell; A) - w \cdot \ell$$

- FOC (assuming interior solution):

$$F_\ell(\ell; A) = w$$
$$F_{A^k}(\ell; A) = 0 \quad \forall k$$

$\rightarrow$ production efficiency is satisfied

- if technology is parameterized (w.l.o.g.) such that it can be subjected to linear taxes then

$$\Pi = F(\ell; A) - w \cdot \ell - \tau \cdot A$$

and FOC

$$F_{A^k}(\ell; A) = \tau^k \quad \forall k$$

Decompose Technological Change

Decomposing the Effects of Technological Change:

- effects of technological change on overall output and on factor owners is given by

$$dy = F_A(\ell; A) \cdot dA$$
$$dw = F_{\ell A}(\ell; A) \cdot dA$$

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Definition (Efficiency-Neutral Technological Change)

For given ℓ, the technology parameter A represents an efficiency-neutral technology choice if $\bar{F}(\ell; A) = y^* \ \forall A$

Decompose Technological Change

Proposition (Decomposition of Technological Change)

For given ℓ, the effects of tech. change dA on factor returns can be decomposed into an efficiency-neutral redistribution between factors that satisfies $\bar{F}_{\ell A} \cdot \ell = 0$ and a proportional scale parameter on all factor returns so that

$$F_{\ell A} = \underbrace{\frac{F_A}{F}}_{\text{scale par.}} \cdot F_\ell + \underbrace{\bar{F}_{\ell A}}_{\text{redistribution}}$$

Proof.

Define $\bar{F}_{\ell A} = F_{\ell A} - F_\ell \cdot F_A / F$ and observe that

$$\bar{F}_{\ell A} \cdot \ell = F_{\ell A} \cdot \ell - F_\ell \cdot \ell \frac{F_A}{F} = F_A - F_A = 0$$

□

Categories of Technological Change

Focus on relative impact:

- technological change is biased towards factor h over factor k if $d\left(w_h/w_k\right)/dA > 0$
  (or Hicks-neutral if factors benefit proportionally)
- in our decomposition, redistribution $\bar{F}_{\ell A}$ captures bias relative to Hicks-neutral progress

Focus on absolute impact:

- factor-saving technological change: $dw^h/dA^k < 0$ or here $F_{\ell^h A^k} < 0$
- factor-using technological change: $dw^h/dA^k > 0$ or here $F_{\ell^h A^k} > 0$

Constrained Planner

Constrained planner setup:

- assume planner cannot redistribute at all so $c^i = w \cdot \ell^i = F_\ell(\ell; A) \cdot \ell^i$
- constrained planner with weights $\{\theta^i\}$ on individual utilities

$$\max_A W = \sum_i \theta^i u^i \left(F_\ell(\ell; A) \cdot \ell^i\right)$$

- FOC

$$\sum_i \theta^i u^{i\prime}\left(c^i\right) F_{\ell A^k}(\ell; A) \cdot \ell^i = 0 \quad \forall k$$

$\rightarrow$ benefit of technology for factors weighted by MU of factor owners

Implement Constrained Planner

- Competitive Equilibrium with taxes (using Euler's theorem):

$$F_{A^k}(\ell; A) = F_{\ell A^k}(\ell; A) \cdot \ell = \tau^k \quad \forall k$$

- Constrained Planner:

$$\sum_i \theta^i u^{i\prime}(c^i) F_{\ell A^k}(\ell; A) \cdot \ell^i = 0 \quad \forall k$$

- in combination

$$\tau^k = -\left(\sum_i \theta^i u^{i\prime}(c^i) F_{\ell A^k}(\ell; A) \cdot \ell^i - E_i u^{i\prime}(c^i) F_{\ell A^k}(\ell; A) \cdot \ell \right)$$
$$= -\sum_h F_{\ell^h A^k}(\ell; A) E_i \left\{ \left[u^{i\prime}(c^i) - E_i u^{i\prime}(c^i) \right] \ell^{hi} \right\}$$

- intuition: tax takes into account
  - how much progress benefits each factor
  - what the relative MU of different agents is
  - and how much of each factor each agent owns

Implement in Practice

Wide variety of angles of implementation:

- create more awareness/"nudge" enterpreneurs/innovators
- government-sponsored research, innovative government programs
- stakeholder participation in decision-making: unions, work councils, ...
- taxes and subsidies on innovation

Factor-Augmenting CES Technology

Example 1: Factor-Augmenting CES Technology:

- two agents: i =worker L, capitalist K
- own one unit of labor L, capital K
- CES production with factor-augmenting technology

$$F(\ell; A) = [(a_K(A)\,\ell_K)^\rho + (a_L(A)\,\ell_L)^\rho]^{\frac{1}{\rho}}$$

- w.l.o.g. parameterize $a_K(A) = A$ so A reflects capital augmentation

Lemma

The market equilibrium will pick a level $A^* = \arg\max_A F(\ell; A)$, *maximizing efficiency*

Factor-Augmenting CES Technology

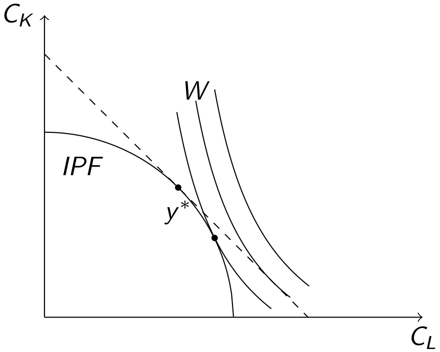

Figure: Innovation possibilities frontier and welfare isoquants

Factor-Augmenting CES Technology

Simple Application to Factor-Augmenting CES Technology:

- ratio of wages to capital rents is

$$\frac{w_L}{w_K} = \left(\frac{a_L(A)}{a_K(A)}\right)^{\rho} = \left(\frac{a_L(A)}{A}\right)^{\rho}$$

- constrained planner chooses

$$\max_A \theta^K u^K \left(w_K(\ell; A)\right) + \theta^L u^L \left(w_L(\ell; A)\right)$$

- optimality condition

$$\frac{\theta^K u^{K\prime}\left(c^K\right)}{\theta^L u^{L\prime}\left(c^L\right)} = -\frac{w_{LA}(\ell; A)}{w_{KA}(\ell; A)}$$

Proposition

The constrained planner generally chooses $A \neq A^*$. If factors are gross complements ($\rho < 0$), the optimal A is strictly increasing in θ^L/θ^K. For gross substitutes, the opposite applies.

Factor-Augmenting Technologies

Examples of factor-augmenting technologies

- for labor:
  - intelligent assistants: complement cognitive abilities of workers
  - platforms that match labor service to reduce idleness?
- for capital:
  - Moore's Law in computing

Automation of Tasks

Example 2: Automation in Task-Based Framework
(loosely inspired by Zeira, 1998; Acemoglu-Restrepo, 2019):

- capitalists and workers with endowments K and L
- production $\log y = \int_0^1 \log y(j)\, dj$ uses unit mass $j \in [0,1]$ of intermediate goods ("tasks")
- fraction $A \in (0,1)$ is automated and performed by capital so

$$y(j) = \begin{cases} K(j) & \text{for } j \in [0,A] \\ L(j) & \text{for } j \in (A,1] \end{cases}$$

- split endowment of K and L over tasks so that $y(j) = K/A$ for $j \le A$ and $y(j) = L/1-A$ for $j > A$
- aggregate production can then be expressed as

$$F(K,L;A) = \left(\frac{K}{A}\right)^A \left(\frac{L}{1-A}\right)^{1-A}$$

Automation of Tasks

- ratio of factor endowments of capital and labor $K/L = \alpha/(1-\alpha)$

Lemma (Production Efficiency)

Production efficiency requires $A = \alpha$.

Proposition (Second-Best)

1. *A constrained planner chooses automation A strictly between θ^K and α.*
2. *An increase θ^L reduces the optimal degree of automation A.*

Automation of Tasks

Broader Thoughts on Task-Based Framework

- power of the framework is that it captures labor-replacing progress (perfect substitution of labor – but within narrow tasks)
- but: how tasks are combined is a tricky question
  - in example above, Cobb-Douglas implies unitary elasticity of substitution $\rightarrow$ efficiency gains in automated tasks are Hicks-neutral
  - if tasks are gross complements (substitutes), efficiency gains in automated tasks benefit (hurt) labor
- unclear that "new tasks" would enter production in the same fashion as opposed to more fundamental changes to productive structure

Investing in Automation

Example 3: Investment in different types of research

- three factors K, L, S where S is skilled labor ("scientists")
- scientists can be deployed to increase overall efficiency A or to automate B

$$F(A, B, K, L) = A^{\alpha}\left[\left(B^{\gamma}K^{1-\gamma}\right)^{\rho} + L^{\rho}\right]^{\frac{1-\alpha}{\rho}}$$

where $A + B = S$

- observe that

$$F_{LA} = \alpha(1-\alpha)A^{\alpha-1}[\cdot]^{\frac{1-\alpha-\rho}{\rho}} L^{\rho-1} > 0$$
$$F_{LB} = (1-\alpha-\rho)(1-\alpha)A^{\alpha}[\cdot]^{\frac{1-\alpha-2\rho}{\rho}} \gamma B^{\gamma\rho-1}K^{(1-\gamma)\rho}L^{\rho-1}$$

- if $\rho > 1-\alpha$ then $F_{LB} < 0$ – if "machines" are sufficiently substitutable for unskilled labor, then allocating more scientists to automation hurts labor

Steering Progress under Imperfect Competition

Example 4: Specialization and Labor's Market Power

- rep firm hires labor $h \in [0,1]$ for a unit mass of tasks

$$y = A(\eta) \int_0^1 \left(\ell^h\right)^{1-\alpha} dh$$

where $\eta \in [0,1]$ reflects the degree of specialization
and $A(\eta) = \left[\underline{A}, \overline{A}\right]$ captures efficiency of production (with Inada):
  - at $\eta = 0$, labor is unspecialized and workers have no market power
  - at $\eta = 1$, each task can be performed only by one worker
- each worker solves

$$\max_{c^i,\ell^i} \frac{\left(c^i\right)^{1-\sigma}}{1-\sigma} - \frac{\left(\ell^i\right)^{1+\psi}}{1+\psi} \quad \text{s.t.} \quad c^i = w\left(\eta \ell^i + (1-\eta)\,\ell^{\setminus i}\right) \cdot \ell^i$$

- labor supply curve

$$w\left(1 - \eta \epsilon_{w,\ell}\right) = \frac{d'\left(\ell^i\right)}{u'\left(c^i\right)} = \left(\ell^i\right)^{\psi}\left(c^i\right)^{\sigma} \quad \text{with} \quad \frac{\partial w}{\partial \eta} > 0$$

Steering Progress under Imperfect Competition

Specialization and Labor's Market Power

- rep firm chooses η to satisfy optimality condition,

$$A'(\eta)\,\ell^{1-\alpha} = w'(\eta)\,\ell$$

Proposition (Steering Progress and Labor's Market Power)

The greater the weight θ^L placed on workers, the more specialized the production technology that the planner will employ.

$\rightarrow$ firms have incentives to make workers more replaceable

Multiple Goods

What goods should we focus innovative efforts on?

In a multiple-goods world there are two additional effects:

1. elasticity of substitution in consumption affects desirability of progress in different sectors
2. with different consumption baskets, changing relative goods prices redistributes real income

→ both need to be considered

Work & Meaning

Some argue that work provides not only income but also non-monetary benefits

- identity
- meaning
- status
- social connections
- autonomy/empowerment

→ important factors for steering technological progress

Setup

Setup to capture non-monetary factor "rents:"

$$U^i = u^i\left(c^i\right) + d^i \qquad \textbf{where} \qquad c^i = F_L(\ell; A) \cdot \ell^i, \; d^i = v(A) \cdot \ell^i$$

- constrained planner's problem

$$\max_A \sum_i \theta^i \left[u^i\left(F_\ell(\ell; A) \cdot \ell^i\right) + v(A) \cdot \ell^i\right]$$

- optimization FOC

$$\sum_i \theta^i \left[u^{i\prime}\left(c^i\right) F_{\ell A^k}(\ell; A) + v_{A^k}\right] \cdot \ell^i = 0 \quad \forall k$$

$$\underbrace{\sum_i \theta^i u^{i\prime}\left(c^i\right) F_{\ell A^k}(\ell; A) \cdot \ell^i}_{\text{factor compensation}} + \underbrace{\sum_i \theta^i v_{A^k} \cdot \ell^i}_{\text{non-monetary}} = 0 \quad \forall k$$

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- constrained planner's problem

$$\max_A \sum_i \theta^i \left[u^i\left(F_\ell\left(\ell; A\right)\cdot \ell^i\right) + v\left(A\right)\cdot \ell^i\right]$$

- optimization FOC

$$\sum_i \theta^i \left[u^{i\prime}\left(c^i\right) F_{\ell A^k}\left(\ell; A\right) + v_{A^k}\right]\cdot \ell^i = 0 \quad \forall k$$

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Corollary

The better we have addressed the material problem (monetary factors), the more steering progress should focus on non-monetary factors

Conclude

Conclusion:

- growing prominence of labor-saving progress, esp. given the rise of AI
- limits to redistribution
- makes steering technological progress increasingly desirable
- and steering progress should also focus on making work more fun