The Economics of Artificial Intelligence: Artificial Intelligence and Economic Growth

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What are the implications of A.I. for economic growth?

- Aghion, Jones, and Jones (2018); also, Acemoglu and Restrepo (2018)
- Growth models with A.I.
  - A.I. helps to make goods
  - A.I. helps to make ideas
- Implications
  - Long-run growth
  - Share of GDP paid to labor vs capital
- Singularity?

Two Main Themes

- A.I. modeled as a continuation of automation
  - Automation = replace labor in particular tasks with machines and algorithms
  - *Past:* textile looms, steam engines, electric power, computers
  - *Future:* driverless cars, paralegals, pathologists, maybe researchers, maybe everyone?
- A.I. may be limited by Baumol's cost disease
  - *Baumol:* growth constrained not by what we do well but rather by what is essential and yet hard to improve

Simple Model of Automation (Zeira 1998)

- Production uses n tasks:

$$Y = AX_1^{\alpha_1} X_2^{\alpha_2} \cdot \ldots \cdot X_n^{\alpha_n},$$

where $\sum_{i=1}^{n} \alpha_i = 1$ and

$$X_{it} = \begin{cases} L_{it} & \text{if not automated} \\ K_{it} & \text{if automated} \end{cases}$$

- Substituting gives

$$Y_t = A_t K_t^{\alpha} L_t^{1-\alpha}$$

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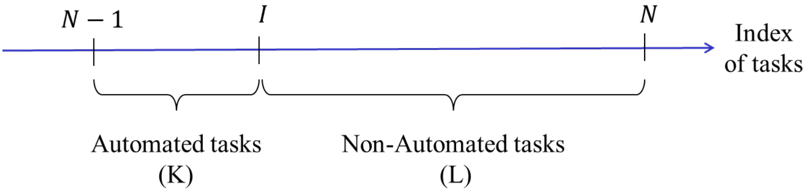
- Comments:
    - α reflects the *fraction* of tasks that are automated
    - Embed in neoclassical growth model $\Rightarrow$

$$g_y = \frac{g_A}{1-\alpha} \quad \text{where} \quad y_t \equiv Y_t/L_t$$

- Automation: $\uparrow \alpha$ raises both capital share and LR growth
- Problem: Hard to reconcile with 20th century
    - Substantial automation but stable growth and capital shares

New Tasks as a Solution

- Acemoglu and Restrepo (2018a, 2018b)
  - Old tasks are gradually automated
  - But new (labor) tasks are created
  - Fraction automated can then be steady
  - Rich framework, with endogenous innovation and automation



Baumol's Cost Disease as a Solution

- Baumol: Agriculture and manufacturing have rapid growth and declining shares of GDP
  - ... but also rising automation
- Aggregate capital share could reflect a balance
  - Rises within agriculture and manufacturing
  - But falls as these sectors decline
- Maybe this is a general feature of the economy!
  - First agriculture, then manufacturing, then services

Model

- Production is CES in tasks, with EofS$<$1 (complements)

$$Y_t = A_t \left(\int_0^1 X_{it}^{\rho}\, di \right)^{1/\rho} \quad \text{where} \quad \rho < 0 \quad \text{(Baumol)}$$

- Let β_t = fraction of tasks automated by date t:

$$Y_t = A_t \left(\int_0^{\beta_t} k_{it}^{\rho}\, di + \int_{\beta_t}^1 l_{it}^{\rho}\, di \right)^{1/\rho}$$

where the total capital stock and labor supply are $K_t = \int_0^{\beta_t} k_{it} di$ and $L_t = \int_{\beta_t}^1 l_{it} di$.

Model

- Symmetric allocations of capital and labor in equilibrium:

$$Y_t = A_t \left[\beta_t \left(\frac{K_t}{\beta_t}\right)^{\rho} + (1-\beta_t)\left(\frac{L}{1-\beta_t}\right)^{\rho}\right]^{1/\rho}$$

$$\implies \quad Y_t = A_t \left((B_t K_t)^{\rho} + (C_t L)^{\rho}\right)^{1/\rho}$$

where $B_t = \beta_t^{\frac{1}{\rho}-1}$ and $C_t = (1-\beta_t)^{\frac{1}{\rho}-1}$

- Note: increased automation $\Rightarrow \downarrow B_t$ and $\uparrow C_t$ since $\rho < 0$.

(e.g. a given amount of capital is spread over more tasks.)

Factor Shares of Income

- Ratio of capital share to labor share:

$$\frac{\alpha_{K_t}}{\alpha_{L_t}} = \left(\frac{\beta_t}{1-\beta_t}\right)^{1-\rho} \left(\frac{K_t}{L_t}\right)^{\rho}$$

- Two offsetting effects ($\rho < 0$):
  - $\uparrow \beta_t$ raises the capital share
  - $\uparrow K_t/L_t$ lowers the capital share

If these balance, constant factor shares are possible

Automation and Asymptotic Balanced Growth

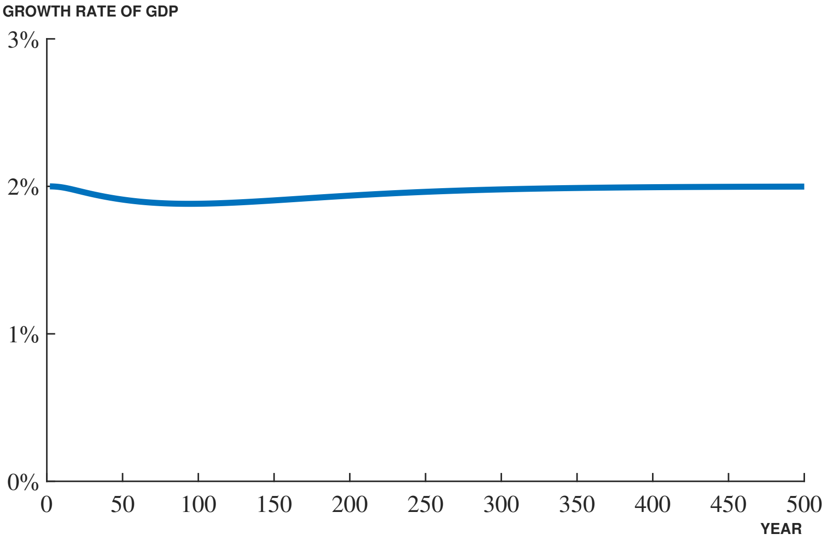
- Suppose a constant fraction of non-automated tasks become automated each period:

$$\dot{\beta}_t = \theta(1 - \beta_t)$$

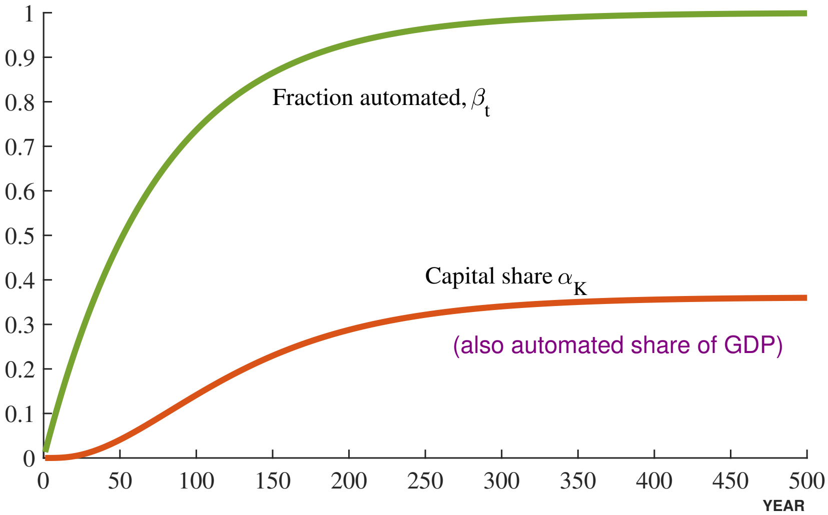
  Then $\beta_t \to 1$ and C_t grows at a constant rate!

- With $Y_t = F(B_t K_t, C_t L_t)$, balanced growth as $t \to \infty$:
  - All tasks eventually become automated
  - Agr/Mfg shrink as a share of the economy...
  - Labor still gets 2/3 of GDP! Vanishing share of tasks, but all else is cheap (Baumol)

Simulation: Automation and Asymptotic Balanced Growth



Simulation: Capital Share and Automation Fraction



Automation and Balanced Growth in 20th Century

- Above argument was asymptotic: we achieved constant capital share in limit as all tasks were automated.
- Yet it seems like most tasks are not automated (historically), and yet we still have a balanced growth path (incl. $\sim$ constant capital share).
- Can we push above model to meet history?

Necessary Condition for Balanced Growth

$$Y_t = F(B_t K_t, A_t L_t)$$

- Uzawa theorem: we must have $B_t = constant$ for balanced growth path. This is usually interpreted as ”technological progress must be labor augmenting.”
- This result has always seemed surprising and odd...!
- Tech advances are often embedded in capital inputs.
- But perhaps these new AI/Automation growth models are giving us a new way to understand technological progress and macroeconomics in general.

Capital-Embodied Innovation

Automation, Baumol, and Balanced Growth

- Consider the automation/AI approach

$$Y_t = s\left[(B_t K_t)^\rho + (A_t L_t)^\rho\right]^{1/\rho}$$

$$B_t = \beta_t^{\frac{1-\rho}{\rho}} Z_t$$

- Automation ($\beta_t \uparrow$) and improving quality of capital ($Z_t \uparrow$) are offsetting in Baumol world ($\rho < 0$).
- Can potentially satisfy Uzawa with all technological progress embodied in capital!
- Exciting area for further research

AI in the Ideas Production Function

- Let production of goods and services be $Y_t = A_t L_t$
- Let idea production be:

$$\dot{A}_t = A_t^{\phi} \left(\int_0^1 X_{it}^{\rho} di \right)^{1/\rho}, \ \rho < 0$$

- Assume fraction β_t of tasks are automated by date t. Then:

$$\dot{A}_t = A_t^{\phi} F(B_t K_t, C_t S_t)$$

where

$$B_t \equiv \beta_t^{\frac{1-\rho}{\rho}}; C_t \equiv (1 - \beta_t)^{\frac{1-\rho}{\rho}}$$

- This is like before...

AI in the Ideas Production Function

- Intuition: with $\rho < 0$ the scarce factor comes to dominate

$$F(B_t K_t, C_t S_t) = C_t S_t \, F\left(\frac{B_t K_t}{C_t S_t}, 1\right) \to C_t S_t$$

- So idea production function becomes

$$\dot{A}_t \to A_t^{\phi} C_t S_t$$

- And asymptotic balanced growth path becomes

$$g_A = \frac{g_C + g_S}{1 - \phi}$$

- We get a “boost” from continued automation (g_C)

Singularities

- Many futurists believe that AI will cause a sharp acceleration of economic growth, or even a ”singularity”
- Consider two types of growth explosions:
  - **Type I:** growth rates increase without bound but remain finite at any point in time.
  - **Type II:** infinite output is achieved in finite time.

Singularities

- **Example 1:** Complete automation of goods and services production.

$$Y_t = A_t K_t$$

$\rightarrow$ Then growth rate can accelerate exponentially

$$g_Y = g_A + sA_t - \delta$$

this would be a “Type I” growth explosion

Singularities

- **Example 2:** Complete automation in ideas production

$$\dot{A}_t = K_t A_t^{\phi}$$

- Intuitively, this idea production function acts like

$$\dot{A}_t = A_t^{1+\phi}$$

- Solution:

$$A_t = \left(\frac{1}{A_0^{-\phi} - \phi t} \right)^{1/\phi}$$

- Thus we can have a true (Type II) **singularity** for $\phi > 0$.
- A_t exceeds any finite value before date $t^* = \frac{1}{\phi A_0^{\phi}}$.

Superintelligence

- Machine intelligence community especially interested in the emergence of a ”superintelligence.”
- Often viewed as recursive process, where a self-improving AI leads to an intelligence explosion.
- This idea can be modeled using similar ideas to those presented above.

$$\dot{A}_{cognitive} = A_{cognitive}^{1+\omega}$$

- If $\omega > 0$, then the process of self-improvement explodes, resulting in an unbounded intelligence in finite time.

Superintelligence

- Even if this happened, would it create singularity in growth?
- Divide tasks into two sets with productivities $A_{physical}$ and $A_{cognitive}$. If physical tasks are essential to producing output ($\rho < 0$), then these will limit growth.
- Question is then really whether a superintelligence can also create an explosion in $A_{physical}$.
  - Yes
$$\dot{A}_{physical} = A_{cognitive}^{\gamma} F(K, L), \; \gamma > 0$$
  - No
$$A_{physical} \leq c$$

Objections to singularities 1: Automation Limits

- For automation of goods and services, we get to an AK model (and Type I growth explosion) if $\beta_t \to 1$.
- Whether A.I. can ultimately perform all essential cognitive tasks needed for production, or more generally achieve human intelligence, is widely debated.
- If not, then growth rates may still be larger with more automation and capital intensity but the labor free singularities featured above become out of reach.

Objections to singularities 2: Search Limits

- Singularities via idea production occur with

$$\dot{A}_t = A_t^{1+\phi} \;\; and \;\; \phi > 0$$

- But the search process itself may be limiting. Fishing out processes suggest that

$$\phi < 0$$

so no singularity via this route.

- A.I. may resolve a problem with the fishermen, but it would not change what is in the pond...

Objections to singularities 2: Search Limits Example

- Example: Let ideas be drawn from a Pareto distribution:

$$f(A_i) = \frac{\beta}{A_i^{\beta+1}}, \;\; A_i > 1, \;\; \beta > 1$$

- Let state of economy be determined by the highest productivity idea yet drawn, A_{max}.
- Idea production function is then

$$\dot{A}_{max} = \theta L_A \times Pr(A_i > A_{max}) \times E[A_i - A_{max} | A_i > A_{max}]$$

Objections to singularities 2: Search Limits Example

- Pareto distribution has nice properties:

$$\dot{A}_{max} = \frac{\theta}{\beta - 1} L_A A_{max}^{1-\beta}$$

- Even if you replace labor with capital (fully automate idea production via A.I.), you have

$$\dot{A}_{max} \sim c A_{max}^{2-\beta}$$

and this (recall $\beta > 1$) isn't enough to get singularity.

Objections to singularities 3: Natural Laws

- Let there be some subset of essential tasks that we can only improve so much. If output is:

$$Y_t = \left(\int_0^1 (a_{it} Y_{it})^\rho \right)^{1/\rho} \quad \text{where } \rho < 0$$

  now can have $a_{it} \to \infty$ for many tasks but no singularity (cf. Moore's Law vs. Carnot's Theorem)

  - *Baumol theme:* growth determined not by what we are good at, but by what is essential yet hard to improve

Conclusion: A.I. in the Production of Goods and Services

- Introduced Baumol's "cost disease" insight into Zeira's model of automation
  - Automation can act like labor augmenting technology (surprise!)
  - Can get balanced growth with a constant capital share well below 100%, even with nearly full automation

Conclusion: A.I. in the Ideas Production Function

- Could A.I. obviate the role of population growth in generating exponential growth?
- Discussed possibility that A.I. could generate a singularity
    - Derived conditions under which the economy can achieve infinite income in finite time
- Discussed obstacles to such events
    - Automation limits, search limits, and/or natural laws (among others)