Artificial Intelligence
and Economic Growth

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in Agrawal et al *The Economics of Artificial Intelligence*, 2019
What are the implications of A.I. for economic growth?

• Build some 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
  ○ Firms and organizations

• 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
Outline

- Basic model: automating tasks in production
- A.I. and the production of new ideas
- Singularity?
- Some facts
The Zeira 1998 Model
Simple Model of Automation (Zeira 1998)

• Production uses $n$ tasks/goods:

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

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

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

- Comments:
  - \( \alpha \) 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
  - Hard to reconcile with 20th century
  - Substantial automation but stable growth and capital shares
Subsequent Work

• Acemoglu and Restrepo (2017, 2018, 2019, 2020, 2021, ...)
  ○ Old tasks are gradually automated as new (labor) tasks are created
  ○ Fraction automated can then be steady
  ○ Rich framework, with endogenous innovation and automation, all cases worked out in great detail

• Peretto and Seater (2013), Hemous and Olson (2016), Agrawal, McHale, and Oettl (2017)
Automation and Baumol’s Cost Disease
Baumol’s Cost Disease and the Kaldor Facts

- 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
Final good

\[ Y_t = \left( \int_0^1 X_{it}^{\frac{\sigma-1}{\sigma}} \, di \right)^{\frac{\sigma}{\sigma-1}} \text{ where } \sigma < 1 \]

Tasks

\[ X_{it} = \begin{cases} 
K_{it} & \text{if automated } \; i \in [0, \beta_t] \\
L_{it} & \text{if not automated } \; i \in [\beta_t, 1] 
\end{cases} \]

Capital accumulation

\[ \dot{K}_t = I_t - \delta K_t \]

Resource constraint (K)

\[ \int_0^1 K_{it} \, di = K_t \]

Resource constraint (L)

\[ \int_0^1 L_{it} \, di = L \]

Resource constraint (Y)

\[ Y_t = Cons_t + I_t \]

Allocation

\[ I_t = \bar{s}_K Y_t \]
Combining equations

\[ Y_t = \left[ \beta_t \left( \frac{K_t}{\beta_t} \right)^{\frac{\sigma - 1}{\sigma}} + (1 - \beta_t) \left( \frac{L}{1 - \beta_t} \right)^{\frac{\sigma - 1}{\sigma}} \right]^{\frac{\sigma}{\sigma - 1}} \]

How \( \beta \) interacts with \( K \): two effects

- \( \beta \): what fraction of tasks have been automated
- \( \beta \): Dilution as \( K/\beta \Rightarrow K \) spread over more tasks

Same for labor: \( L/(1 - \beta_t) \) means given \( L \) concentrated on fewer tasks, raising “effective labor”
Rewriting in classic CES form

- Collecting the $\beta$ terms into factor-augmenting form:

$$Y_t = F(B_tK_t, C_tL_t)$$

where

$$B_t = \left(\frac{1}{\beta_t}\right)^{\frac{1}{1-\sigma}} \quad \text{and} \quad C_t = \left(\frac{1}{1-\beta_t}\right)^{\frac{1}{1-\sigma}}$$

- Effect of automation: $\uparrow \beta_t \Rightarrow \downarrow B_t$ and $\uparrow C_t$

*Intuition: dilution effects just get magnified since $\sigma < 1$*
Automation

• Suppose a constant fraction of non-automated tasks get automated every period:

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

\[ \Rightarrow \beta_t \to 1 \]

• What happens to \(1 - \beta_t =: m_t\)?

\[ \frac{\dot{m}_t}{m_t} = -\theta \]

*The fraction of labor-tasks falls at a constant exponential rate*
Putting it all together

\[ Y_t = F(B_t K_t, C_t L_t) \] where \[ B_t = \left( \frac{1}{\beta_t} \right)^{1-\sigma} \] and \[ C_t = \left( \frac{1}{1 - \beta_t} \right)^{1-\sigma} \]

- \( \beta_t \to 1 \Rightarrow B_t \to 1 \)

- But \( C_t \) grows at a constant exponential rate!

\[ \frac{\dot{C}_t}{C_t} = -\frac{1}{1 - \sigma} \frac{\dot{m}_t}{m_t} = \frac{\theta}{1 - \sigma} \]

- When a constant fraction of remaining goods get automated and \( \sigma < 1 \), the automation model features an asymptotic BGP that satisfies Uzawa
Factor Shares of Income

- Ratio of capital share to labor share:

\[
\frac{\alpha_K}{\alpha_L} = \left( \frac{\beta_t}{1 - \beta_t} \right)^{1/\sigma} \left( \frac{K_t}{L_t} \right)^{\frac{\sigma-1}{\sigma}}
\]

- Two offsetting effects ($\sigma < 1$):
  - $\uparrow \beta_t$ raises the capital share
  - $\uparrow K_t/L_t$ lowers the capital share

**These balance and deliver constant factor shares in the limit**

\[
\alpha_{Kt} \equiv \frac{F_K}{Y} = \beta_t^{1/\sigma} \left( \frac{K_t}{Y_t} \right)^{\frac{\sigma-1}{\sigma}} \rightarrow \left( \frac{\bar{s}_K}{\bar{g}Y + \delta} \right)^{\frac{\sigma-1}{\sigma}} < 1
\]
Intuition for AJJ result

• Why does automation lead to balanced growth and satisfy Uzawa?
  o $\beta_t \rightarrow 1$ so the KATC piece “ends” eventually (all tasks automated)
  o Labor per task: $L/(1 - \beta_t)$ rises exponentially over time!
  o Constant population, but concentrated on an exponentially shrinking set of goods
    $\Rightarrow$ exponential growth in “effective” labor

• Baumol logic
  o Agr/Mfg shrink as a share of the economy...
  o Labor still gets 2/3 of GDP! Vanishing share of tasks, but all else is cheap
    (Baumol)

Interesting question: What fraction of tasks automated today? $\beta_{2022}$
(B. Jones and X. Liu 2022 on capital-embodied technical change)
Simulation: Automation and Asymptotic Balanced Growth

GROWTH RATE OF GDP

YEAR

0% 1% 2% 3%

0 50 100 150 200 250 300 350 400 450 500
Simulation: Capital Share and Automation Fraction

Fraction automated, $\beta_t$

Capital share $\alpha_K$

(also automated share of GDP)
Constant Factor Shares?

- Consider $g_A > 0$ — technical change beyond just automation
- Alternatively, factor shares can be constant if automation follows

$$g_{\beta t} = (1 - \beta_t) \left( \frac{-\rho}{1 - \rho} \right) g_{kt},$$

- Knife-edge condition...
- Surprise: growth rates increase not decrease. Why? Requires

$$g_{Yt} = g_A + \beta_t g_{Kt}.$$

- $g_A = 0$ means zero growth. $g_A > 0$ means growth rises
Simulation: Constant Capital Share

Fraction automated, $\beta_t$

Capital share $\alpha_K$

YEAR
0 50 100 150 200 250 300
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7

21
Simulation: Constant Capital Share

GROWTH RATE OF GDP

YEAR

22
Simulation: Switching regimes...

GROWTH RATE OF GDP

YEAR
Simulation: Switching regimes...

Fraction automated, $\beta_t$

Capital share $\alpha_K$
A.I. and Ideas
AI in the Ideas Production Function

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

$$
\dot{A}_t = A_t^\phi \left( \int_0^1 X_{it}^{\frac{\sigma - 1}{\sigma}} \, di \right)^{\frac{\sigma}{\sigma - 1}}, \sigma < 1
$$

- Assume fraction $\beta_t$ of tasks are automated by date $t$. Then:

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

where

$$
B_t = \left( \frac{1}{\beta_t} \right)^{\frac{1}{1 - \sigma}} \quad \text{and} \quad C_t = \left( \frac{1}{1 - \beta_t} \right)^{\frac{1}{1 - \sigma}}
$$

- This is like before...
AI in the Ideas Production Function

- Intuition: with $\sigma < 1$ the scarce factor comes to dominate

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

- So, with continuous automation

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

- And asymptotic balanced growth path becomes

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

- We get a “boost” from continued automation ($g_C$)
Can automation replace population growth?

• Maybe! Suppose $S$ is constant, $g_S = 0$
  ◦ Intuition: Fixed $S$ is spread among exponentially-declining measure of tasks
  ◦ So researchers per task is growing exponentially!

• However
  ◦ This setup takes automation as exogenous and at “just the right rate”
  ◦ What if automation is endogenized?
  ◦ Is population growth required to drive automation?
  ◦ Could a smart/growing AI entirely replace humans?
Singularities
Now we become more radical and consider what happens when we go “all the way” and allow AI to take over all tasks.

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

\[ Y_t = A_t K_t \]

→ Then growth rate can accelerate exponentially

\[ g_Y = g_A + sA_t - \delta \]

we call this a “Type I” growth explosion
Singularities: Example 2

- Complete automation in ideas production function

\[ \dot{A}_t = K_t A_t^\phi \]

- 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 \textbf{singularity} for \( \phi > 0 \). \( A_t \) exceeds any finite value before date \( t^* = \frac{1}{\phi A_0^\phi} \).
Singularities: Example 3 – Incomplete Automation

- Cobb-Douglas, $\alpha$ and $\beta$ are fraction automated, $S$ constant
  
  \[ \dot{K}_t = \bar{s}L^{1-\alpha}A_t^\sigma K_t^\alpha - \delta K_t. \]
  
  \[ \dot{A}_t = K_t^\beta S^\lambda A_t^\phi \]

- Standard endogenous growth requires $\gamma = 1$:
  
  \[ \gamma := \frac{\sigma}{1 - \alpha} \cdot \frac{\beta}{1 - \phi}. \]

- If $\gamma > 1$, then growth explodes!
  - Can occur without full automation
  - Example: $\alpha = \beta = \phi = 1/2$ and $\sigma > 1/2$. 
Objections to singularities

1. Automation limits (no $\beta_t \to 1$)

2. Search limits

$$\dot{A}_t = A_t^{1+\phi} \quad \text{or even} \quad A_t \leq \bar{A}$$

but $\phi < 0$ (e.g., fishing out, burden of knowledge...)

3. Natural Laws

$$Y_t = \left( \int_0^1 (a_{it} Y_{it})^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad \text{where} \quad \sigma < 1$$

now can have $a_{it} \to \infty$ for many tasks but no singularity

- Baumol theme: growth determined not by what we are good at, but by what is essential yet hard to improve
Final Thoughts
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)
Extra Slides
Some Facts
Capital Shares in U.S. Industries

- Movies
- Air Trans.
- Publishing
- Wholesale
- Retail
Capital Shares in U.S. Industries

Telecommunications

Federal Govt

Health (hospitals)

Health (ambulatory)

Education
Adoption of Robots and Change in Capital Share

Motor Vehicles = 56% of robot investment in 2014
AI, Organizations, and Wage Inequality

- Usual story: robots replace low-skill labor, hence ↑ skill premium (e.g., Krusell et al. 2000)
- But solving future problems, incl. advancing AI, might be increasingly hard, suggesting ↑ complementarities across workers, ↑ teamwork, and changing firm boundaries (Garicano 2000, Jones 2009)
- Aghion et al. (2017) find evidence along these lines
  - outsource higher fraction of low-skill workers
  - pay increased premium to low-skill workers kept
AI, Organizations, and Wage Inequality

![Graph](image-url)

Log wage relative to labour market mean vs. In R&D intensity.

kernel = epanechnikov, degree = 0, bandwidth = .31, pwidth = .47
AI, Skills, and Wage Inequality

![Graph showing the relationship between log wage relative to labor market mean and In R&D intensity for low, medium, and high skill levels.](image)