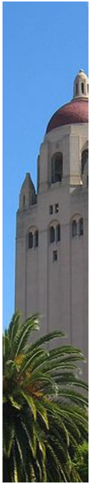


Artificial Intelligence and Economic Growth

P. Aghion, B. Jones, and C. Jones

in Agrawal et al *The Economics of Artificial Intelligence*, 2019

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

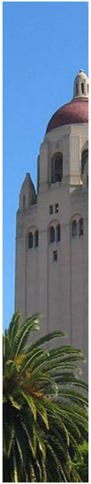
- Build some growth models with A.I.
  - A.I. helps to make goods
  - A.I. helps to make ideas
- Implications
  - Long-run growth
  - Share of GDP paid to labor vs capital
  - Firms and organizations
- Singularity?

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

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

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

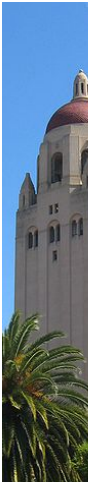
- Comments:
  - α reflects the *fraction* of tasks that are automated
  - Embed in neoclassical growth model $\Rightarrow$

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

- Automation: $\uparrow \alpha$ raises both capital share and LR growth
  - 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

AJJ Economic Environment

Final good $$Y_t = \left(\int_0^1 X_{it}^{\frac{\sigma-1}{\sigma}} \, di \right)^{\frac{\sigma}{\sigma-1}} \quad \text{where} \quad \sigma < 1$$

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

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 $$I_t = \bar{s}_K Y_t$$

Automation and growth

- 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 β interacts with K: two effects
  - β: what fraction of tasks have been automated
  - β: 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 β terms into factor-augmenting form:

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

where

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

- 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:

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

$$\Rightarrow \quad \beta_t \to 1$$

- 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

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

- $\beta_t \to 1 \Rightarrow B_t \to 1$
- 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:

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

- 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

$$\alpha_{Kt} \equiv \frac{F_K K}{Y} = \beta_t^{\frac{1}{\sigma}} \left(\frac{K_t}{Y_t}\right)^{\frac{\sigma-1}{\sigma}} \rightarrow \left(\frac{\bar{s}_K}{g_Y+\delta}\right)^{\frac{\sigma-1}{\sigma}} < 1$$

Intuition for AJJ result

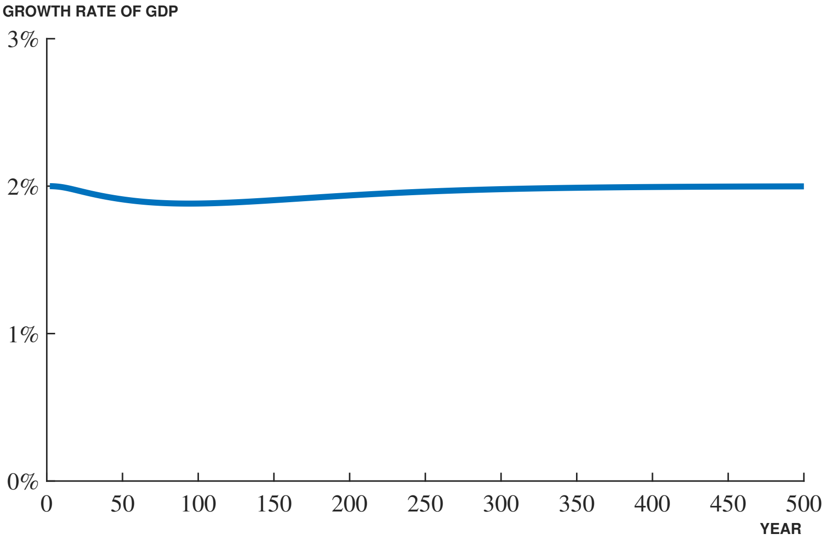
- Why does automation lead to balanced growth and satisfy Uzawa?
  - $\beta_t \to 1$ so the KATC piece "ends" eventually (all tasks automated)
  - Labor per task: $L/(1-\beta_t)$ rises exponentially over time!
  - Constant population, but concentrated on an exponentially shrinking set of goods $\Rightarrow$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

- Baumol logic
  - 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)

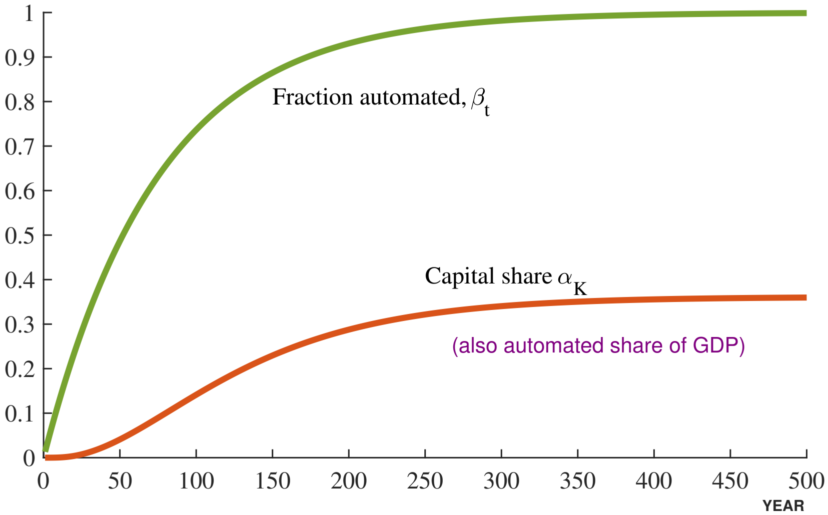
Interesting question: What fraction of tasks automated today? β_{2022}

(B. Jones and X. Liu 2022 on capital-embodied technical change)

Simulation: Automation and Asymptotic Balanced Growth



Simulation: Capital Share and Automation Fraction



Constant Factor Shares?

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

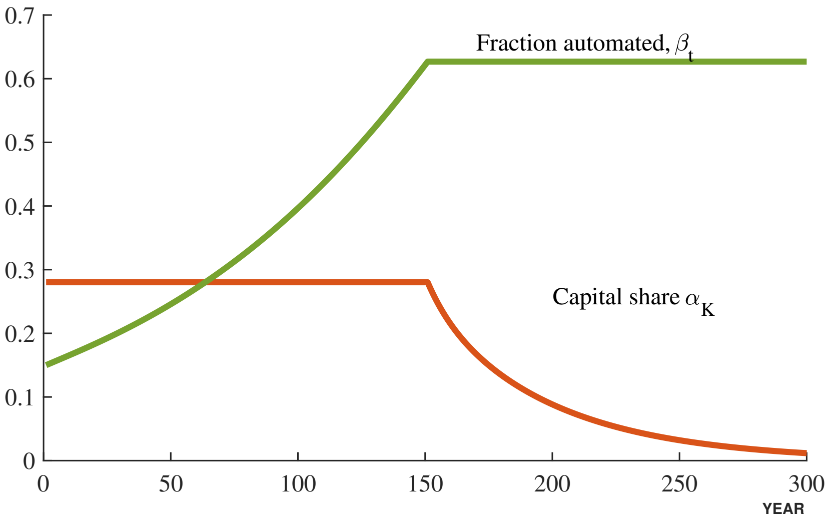
$$g_{\beta t} = (1 - \beta_t) \left(\frac{-\rho}{1 - \rho} \right) g_{kt},$$

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

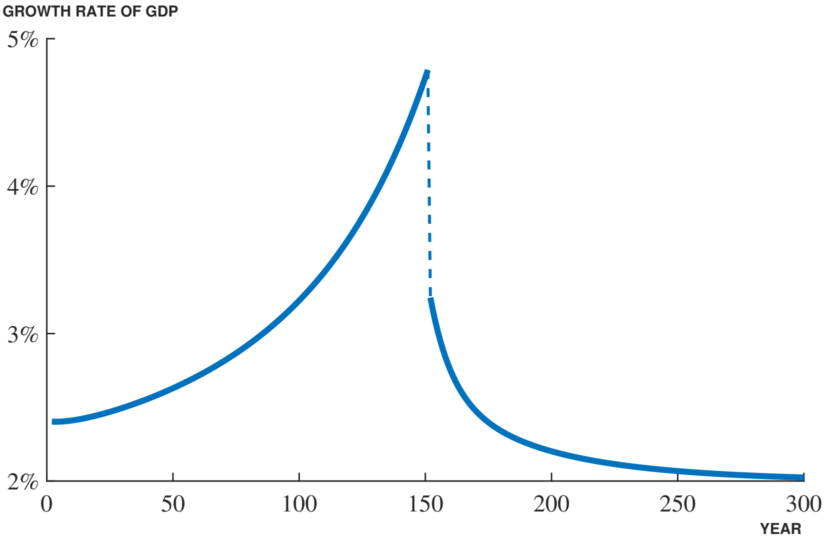
$$g_{Yt} = g_A + \beta_t g_{Kt}.$$

- $g_A = 0$ means zero growth. $g_A > 0$ means growth rises

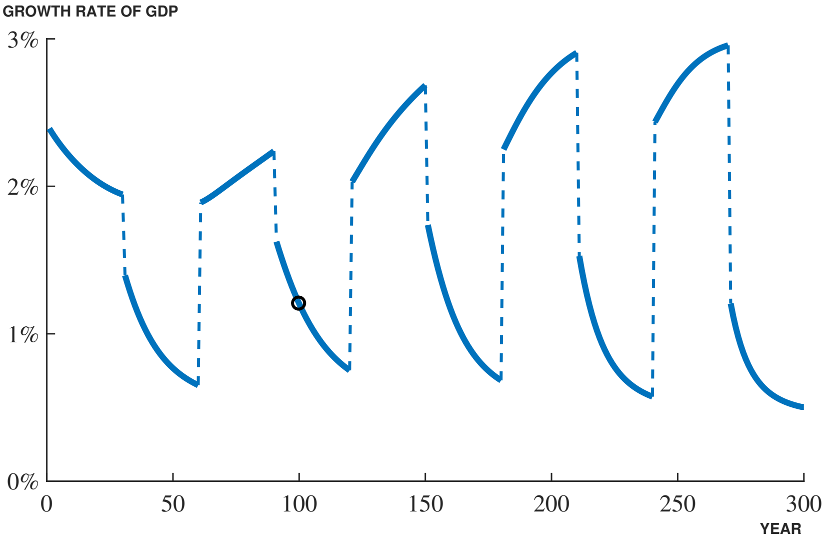
Simulation: Constant Capital Share



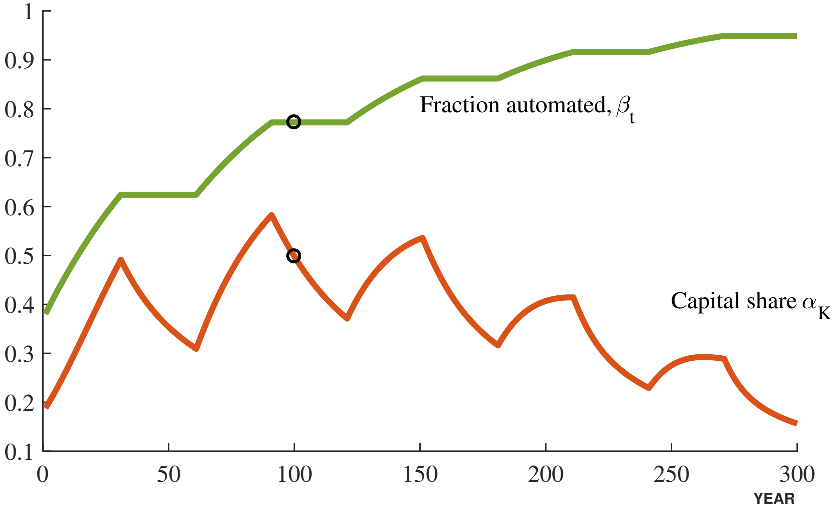
Simulation: Constant Capital Share

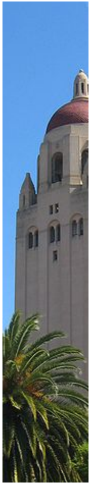


Simulation: Switching regimes...



Simulation: Switching regimes...





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 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

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

- This is like before...

AI in the Ideas Production Function

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

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

- So, with continuous automation

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

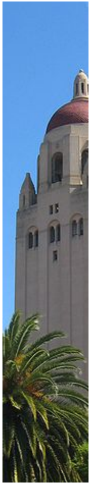
- And asymptotic balanced growth path becomes

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

- 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

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.

$$Y_t = A_t K_t$$

$\rightarrow$ 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 **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, α and β 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

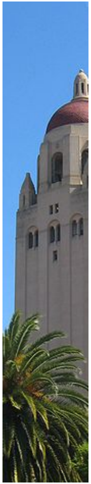
1. Automation limits (no $\beta_t \to 1$)
2. Search limits

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

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

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

   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

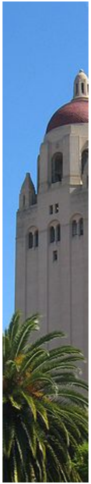
Conclusion: A.I. in the Production of Goods and Services

- 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

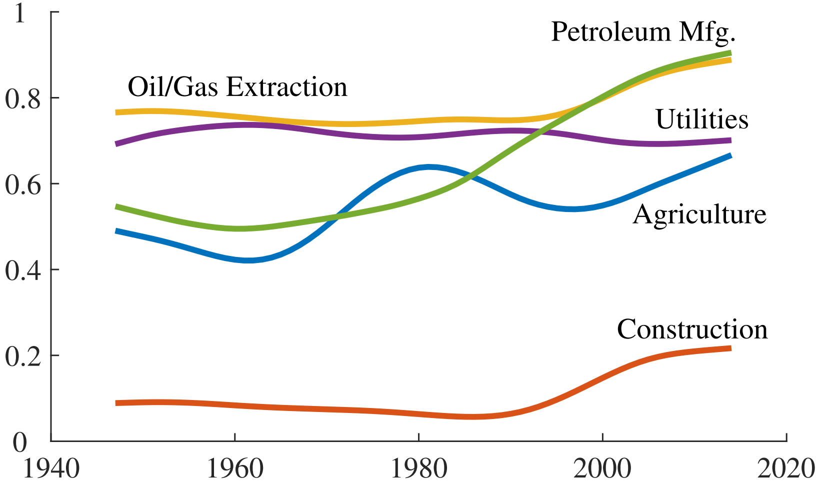
- Could A.I. obviate the role of population growth in generating exponential growth?
- Discussed possibility that A.I. could generate a singularity
  - Derived conditions under which the economy can achieve infinite income in finite time
- Discussed obstacles to such events
  - Automation limits, search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

Extra Slides

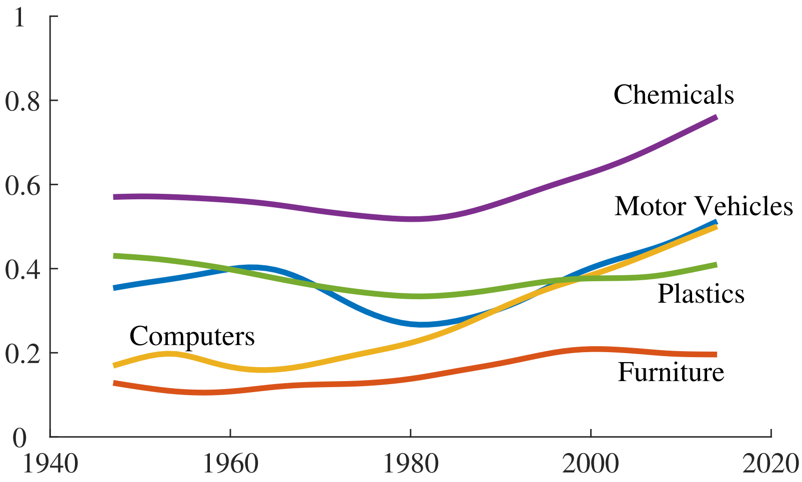


Some Facts

Capital Shares in U.S. Industries



Capital Shares in U.S. Industries



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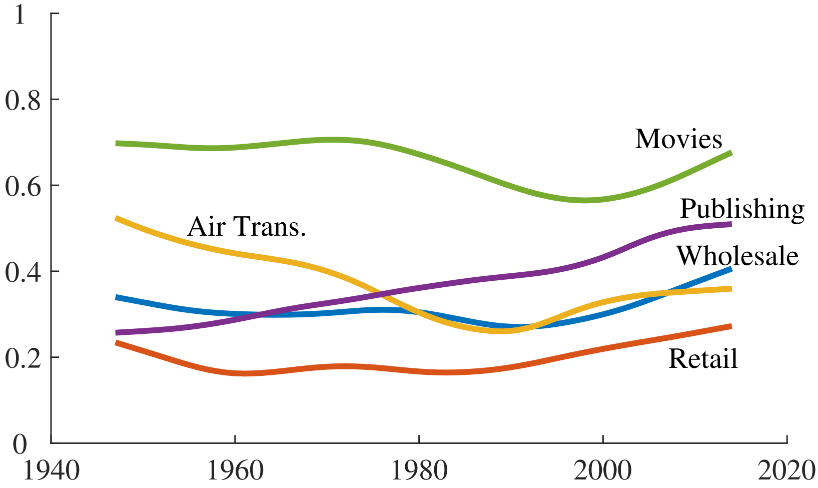

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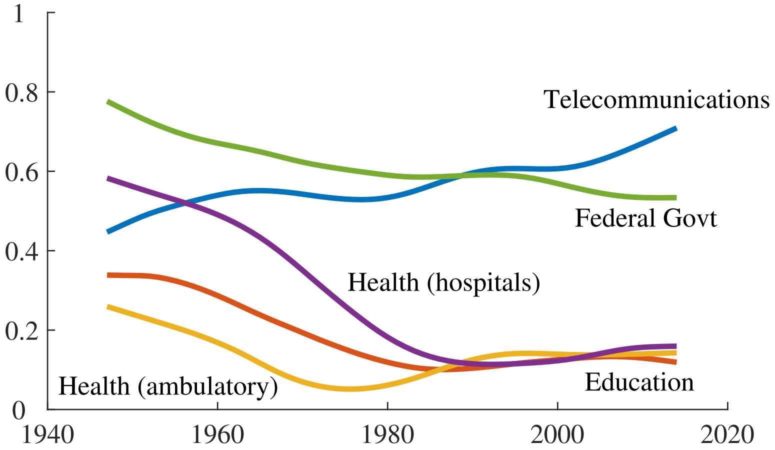
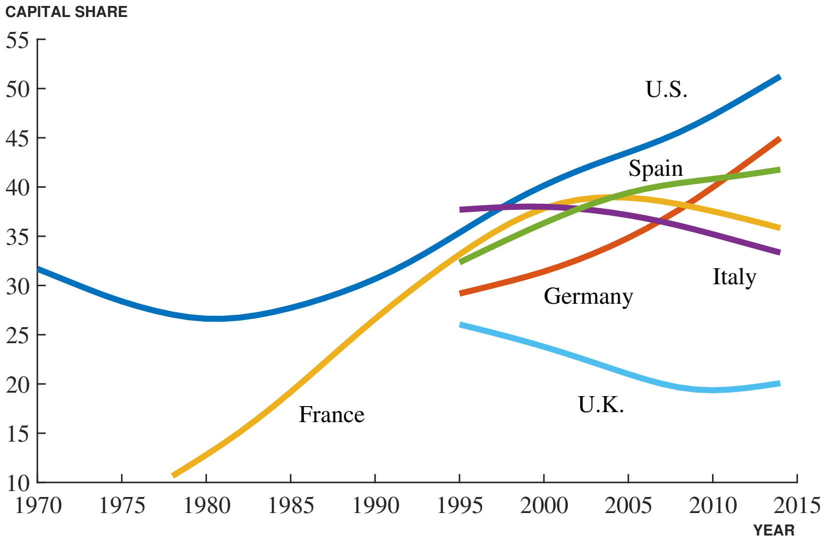
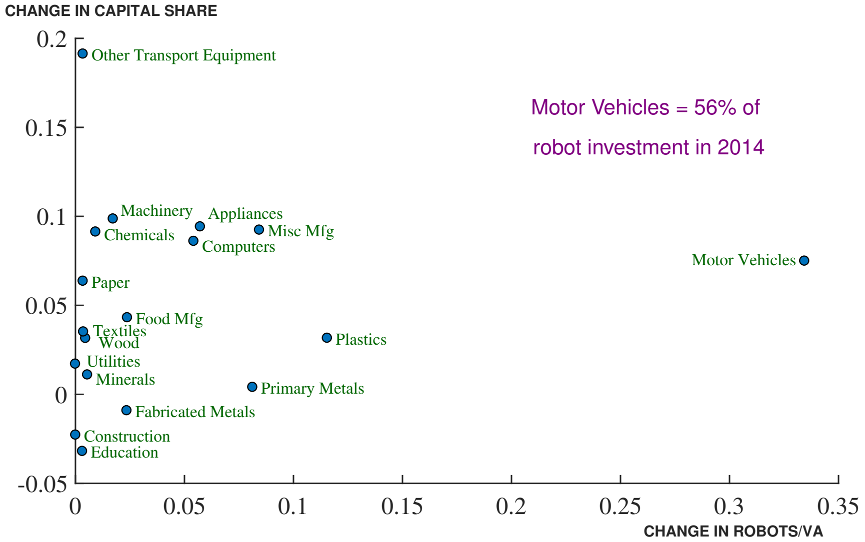


Capital Share of Income: Transportation Equipment



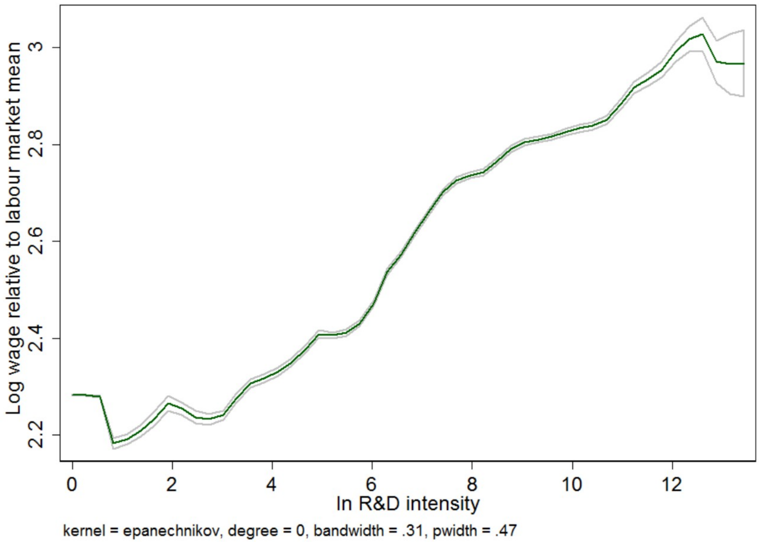
Adoption of Robots and Change in Capital Share



AI, Organizations, and Wage Inequality

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

AI, Organizations, and Wage Inequality



AI, Skills, and Wage Inequality