Capital-Skill Complementarity and Inequality

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Capital-Skill Complementarity

- Griliches (REStat 1969)
- Valuable insight to interpret inequality dynamics in the US and globally
- Macroeconomic perspective: aggregate production function
- Outline
    1. The hypothesis: theory and data
    2. Relationship with SBTC
    3. KSC in use or in adoption of new capital?
    4. Quasi-experimental micro evidence
    5. Skills vs tasks
    6. Global inequality trends

A Two-Sector Model of the Macroeconomy

- Greenwood, Hercowitz and Krusell (AER 1998)

$$\begin{aligned} c_t &= A_{ct} F\left(k_{ct}, \mathbf{l}_{ct}\right) \\ i_t &= A_{it} F\left(k_{it}, \mathbf{l}_{it}\right) \end{aligned}$$

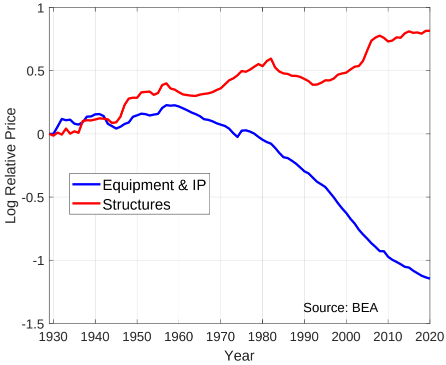
- Key: $A_{ct} \neq A_{it}$, i.e., sector-specific technical change
- Assume F is CRS, factors are fully mobile, and markets are competitive
- Can represent this economy through an aggregate production function:

$$c_t + i_t q_t = A_{ct} F\left(k_t, \mathbf{l}_t\right), \quad \text{where} \quad q_t = \frac{A_{ct}}{A_{it}}$$

1. q_t^{-1} is the rate of investment-specific technical change
2. q_t is also the price of investment relative to consumption

Relative Price of Capital

- Important: distinguish between structures and equipment & IP



- Fact: q_t started declining around 1960, accelerated since 1980, and slowed down since 2010

- Key observation to interpret dynamics of income inequality in the US

Capital-Skill Complementarity Hypothesis

- Three steps:

    1. Rapid decline in the relative price of equipment increased the relative demand for capital

    2. Skilled labor is a complement of capital equipment in production, whereas unksilled labor is a substitute

    3. Due to these patterns of substitutability, this technological force pushed up the skill premium

- Implementation: must take a stand on functional form specification for F

- Key: distinguish (1) between capital equipment and structures, (2) and between skilled and unskilled labor (education),

Aggregate Production Function

- Krusell, Ohanian, Rios-Rull and Violante (ECA 2000)

$$\begin{aligned} Y_t &= A_t F\left(K_{st}, K_{et}, S_t, U_t\right) \\ &= A_t K_{st}^{\alpha}\left[\mu U_t^{\sigma} + (1-\mu)\underbrace{\left[\lambda K_{et}^{\rho} + (1-\lambda) S_t^{\rho}\right]^{\frac{\sigma}{\rho}}}_{X_t}\right]^{\frac{1-\alpha}{\sigma}} \end{aligned}$$

- Elasticity of substitution between (K_e, S) is $\frac{1}{1-\rho}$
- Elasticity of substitution between (X, U) is $\frac{1}{1-\sigma}$

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- Elasticity of substitution between (K_e, S) is $\frac{1}{1-\rho}$
- Elasticity of substitution between (X, U) is $\frac{1}{1-\sigma}$
- How should we formally define 'capital-skill complementarity'?
  - Fallon and Layard (JPE 1985)
  - Two definitions, both implying $\sigma > \rho$

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Two Formal Definitions of K-S Complementarity

1. *A rise in K_e increases the marginal product (wage) of S more than the marginal product (wage) of U*

    - S is a stronger (Hicks) q-complement than U with K_e

Two Formal Definitions of K-S Complementarity

1. *A rise in K_e increases the marginal product (wage) of S more than the marginal product (wage) of U*

    - S is a stronger (Hicks) q-complement than U with K_e

2. *A fall in q increases the demand for S more than the demand for U*

    - S is a stronger (Allen) p-complement than U with K_e

Both definitions are true when $\sigma > \rho$

Implications for Wage Inequality

- Skill premium implied by the model:

$$\log\left(\frac{w_{st}}{w_{ut}}\right) = \text{const} + \underbrace{\frac{\sigma-\rho}{\rho}\log\left[\lambda\left(\frac{K_{et}}{S_t}\right)^{\rho} + (1-\lambda)\right]}_{\text{K-S complementarity}} - \underbrace{(1-\sigma)\log\left(\frac{S_t}{U_t}\right)}_{\text{skill abundance}}$$

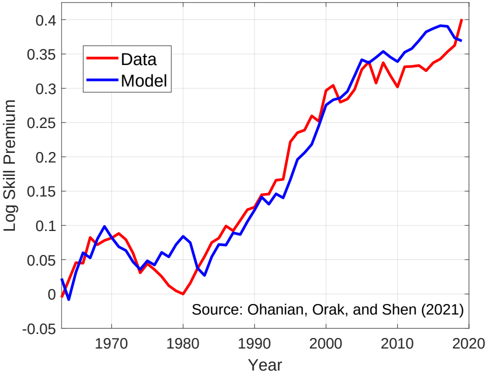
- In the data:

1. $K_{et}/S_t \uparrow \quad \Rightarrow \quad$ when $\sigma > \rho$, KSC term raises skill premium

2. $S_t/U_t \uparrow \quad \Rightarrow \quad$ skill abundance always lowers skill premium

Estimation on Aggregate Data (1963-2019)

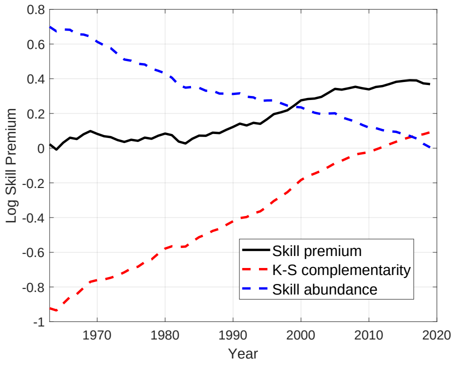
- Model parameters are estimated based on several moment conditions



- $\hat{\sigma} = 0.55\ (0.05)$ and $\hat{\rho} = -.45\ (0.06)$ $\Rightarrow$ K-S complementarity

Decomposition of the Skill Premium

$$\log\left(\frac{w_{st}}{w_{ut}}\right) = \text{const} + \underbrace{\frac{\sigma-\rho}{\rho}\log\left[\lambda\left(\frac{K_{et}}{S_t}\right)^{\rho} + (1-\lambda)\right]}_{\text{K-S complementarity}} - \underbrace{(1-\sigma)\log\left(\frac{S_t}{U_t}\right)}_{\text{skill abundance}}$$



- K-S complementarity acts as a skill-biased demand shifter

K-S complementarity vs SBTC

- Skill premium under SBTC

$$\log\left(\frac{w_{st}}{w_{ut}}\right) = \underbrace{\sigma\gamma \cdot t}_{\text{SBTC}} - (1-\sigma)\log\left(\frac{S_t}{U_t}\right)$$

- Skill premium under K-S complementarity (log-appx.)

$$\log\left(\frac{w_{st}}{w_{ut}}\right) \simeq \lambda\frac{\sigma-\rho}{\rho}\left(\frac{K_{et}}{S_t}\right)^{\rho} - (1-\sigma)\log\left(\frac{S_t}{U_t}\right)$$

- K-S complementarity offers a microfoundation to SBTC
  1. It replaces an unobservable trend with observables
  2. It gives economic content to SBTC

K-S Complementarity vs SBTC

- Models are nested: can be easily tested against each other

$$\log\left(\frac{w_{st}}{w_{ut}}\right) \simeq \lambda\frac{\sigma-\rho}{\rho}\left(\frac{K_{et}}{S_t}\right)^{\rho} + \sigma\gamma\cdot t - (1-\sigma)\log\left(\frac{S_t}{U_t}\right)$$

$\hat{\sigma}$	$\hat{\rho}$	$\hat{\gamma}$
0.434**	−0.522**	0.020
(0.173)	(0.181)	(0.036)

K-S Complementarity vs SBTC

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(0.173)	(0.181)	(0.036)

- Acemoglu's (JEL 2002) critique: in this regression

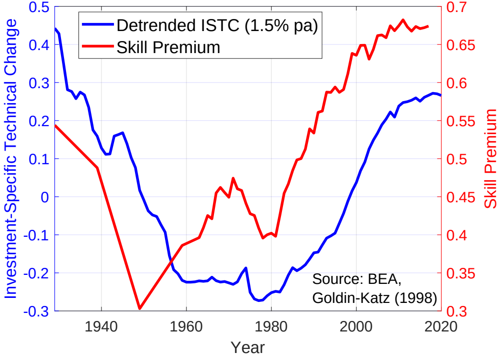
$$\log\left(\frac{w_{st}}{w_{ut}}\right) = \beta \cdot q_t + \sigma\gamma \cdot t - (1-\sigma)\log\left(\frac{S_t}{U_t}\right)$$

  the time trend makes the relative price of capital q_t not significant

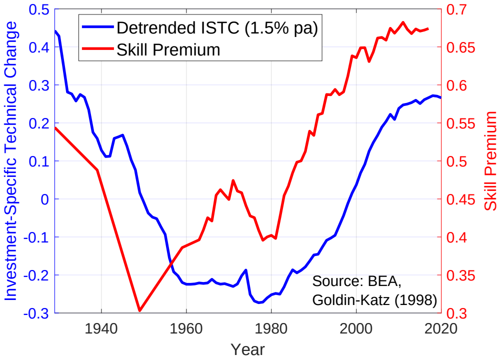
- But this regression is not the one implied by the KSC model

- In fact, q_t insignificant even when true DGP is the KSC model!

A Longer-Run Perspective on the KSC Hypothesis



A Longer-Run Perspective on the KSC Hypothesis



- What are the origins of KSC? (Goldin-Katz, QJE 1998; Mitchell, IER 2005)
- 19th century: no trace, rather, K-S substitution in manufacturing
- 1920s-30s: emergence of K-S complementarity
    - shift from assembly line toward continuous and batch processes

Alternative Formulation: Complementarity in Adoption

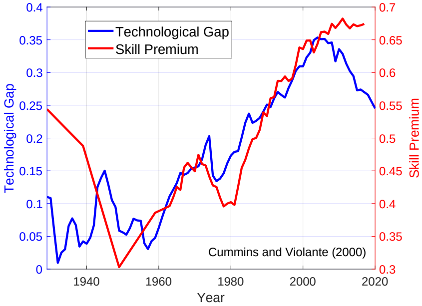
- Nelson-Phelps (AER 1966), Caselli (AER 1997), Greenwood-Yorukoglu (1997), Galor and Moav (QJE 2000), Aghion-Howitt-Violante (JEG 2002)
- Skills allow workers to adapt to a new technological environment
- K and S are complementary only in adoption phase of new technology
- Effect on the skill premium is transitory
- Are K and S complementary in adoption or in use?
    - Chun (RESTat 2005) exploits US cross-industry variation in age and quantity of IT capital, and concludes use is more important than adoption in driving dynamics of the skill premium

Technological Gap and Skill Premium

- Hulten's (AER 1992) notion of technological gap
- Gap between productivity of new investment and that of existing capital

$$\text{Technological Gap} = \frac{\phi_t - \Phi_t}{\Phi_t}$$

  - $\phi_t = q_t^{-1}$: rate of investment-specific technical change
  - $\Phi_t = \frac{\sum_{j=0}^{t}(1-\delta)^j \phi_{t-j}\, i_{t-j}}{\sum_{j=0}^{t}(1-\delta)^j\, i_{t-j}}$: technology embodied in existing K stock



‘Causal’ Micro Evidence on K-S Complementarity

- Akerman, Gaarder, and Mogstad (QJE 2015). *The skill complementarity of broadband internet* ✓
  - Staggered adoption of broadband internet across regions
- Acemoglu and Finkelstein (JPE 2008). *Input and Technology Choices in Regulated Industries: Evidence from the Health Care Sector* ✓
  - Policy-induced decline in the relative price of capital
- Lewis (QJE 2011). *Immigrations, Skill Mix and Capital-Skill Complementarity* ✓
  - Local variation in migration flows of unskilled labor
- Curtis, Garrett, Ohrn, Roberts, and Suarez Serrato (WP 2022). *Capital Investment and Labor Demand* ×
  - Variation in depreciation bonus across manufacturing plants
  - Contrarian result: K_e and production workers are p-complement

KSC in the Micro and in the Macro

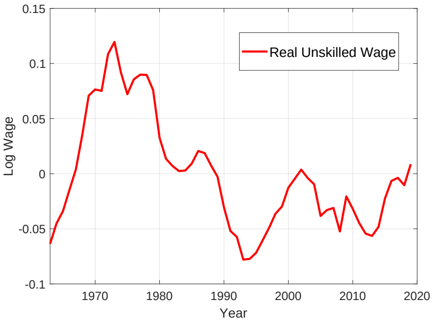
- Can we reconcile the fact that (apparently) some sectors of the economy do not display KSC, while aggregate data do?
- Yes, through equilibrium aggregation, especially if the sector w/o KSC is small and shrinking like manufacturing
- Example: 2 goods, 2 inputs with same cost share, CRS production and free mobility of factors

$$
\begin{aligned}
y_1 &= f(k_1, l_1) && [\text{share}_1 \text{ small} \quad \& \quad \varepsilon_{k_1,l_1} > 0] \\
y_2 &= g(k_2, l_2) && [\text{share}_2 \text{ large} \quad \& \quad \varepsilon_{k_2,l_2} < 0] \\
y &= h(y_1, y_2) \\
\Rightarrow \varepsilon_{k,l} &= \text{share}_1 \cdot \varepsilon_{k_1,l_1} + \text{share}_2 \cdot \varepsilon_{k_2,l_2} < 0
\end{aligned}
$$

- Berlingieri-Boeri-Lashkari-Vogel (WP, 2022): reallocation of output toward firms with stronger KSC is quantitatively important

A Challenge for the KSC Hypothesis?

- KSC struggles to explain why real unskilled wages stagnated



- It predicts growing real unskilled wage
  - Why? In the specification for F, K_e is q-complement with U

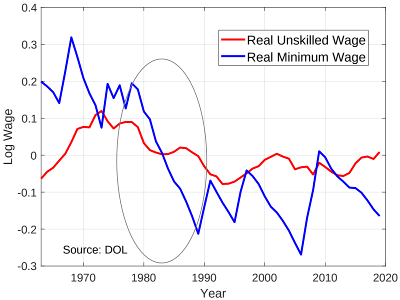
Three Possible Solutions

1. Stagnant TFP in the C sector
   - Still consistent with aggregate growth because of ISTC

2. Different nesting, e.g. a case where $\frac{\partial \log F_U}{\partial \log K_e} < 0$ is:

$$Y_t = A_t K_{st}^{\alpha} S_t^{\mu} \left[\lambda K_{et} + (1-\lambda) U_t\right]^{1-\alpha-\mu}$$

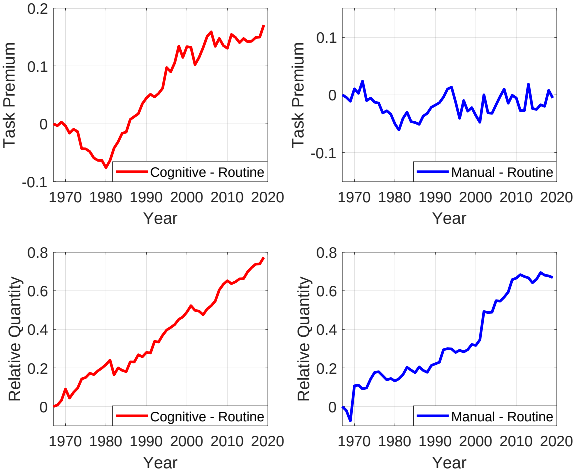
3. Role of labor market institutions (e.g., Lee QJE 1999)



From Skills to Tasks

- Alternative version of the model where labor is classified based on task
  - Autor-Levy-Murnane (QJE 2003), Acemoglu-Autor (HLE 2011)
- Three groups of tasks:
  1. Cognitive (non-routine): e.g., manager, engineer
  2. Routine: e.g., machine operator, bank teller
  3. Manual: e.g., janitor, gardener
- Fact: different employment and wage dynamics across groups

Relative Wages and Employment by Task



- Sharp rise in the task premium of C labor
- Polarization in employment: C and M labor $\uparrow$ relative to R

Capital-Task Complementarity (Orak, 2020)

$$Y_t = A_t K_t^{\alpha} \left[\mu R_t^{\sigma} + (1-\mu) \left[\left(\lambda K_{et}^{\rho} + (1-\lambda) C_t^{\rho} \right)^{\frac{\theta}{\rho}} M_t^{1-\theta} \right]^{\sigma} \right]^{\frac{1-\alpha}{\sigma}}$$

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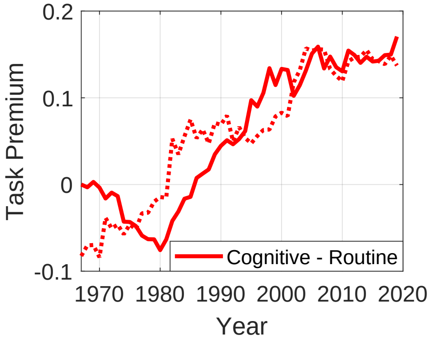

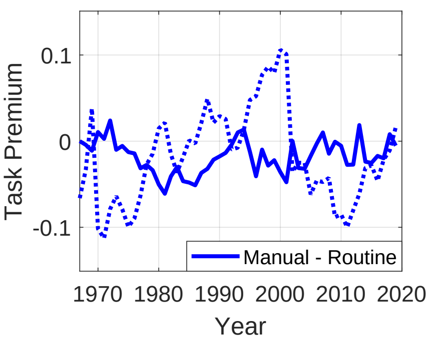

- Estimates: $\hat{\sigma} = 0.45 \quad \hat{\rho} = -0.22 \quad \Rightarrow$ K-C complementarity

Global Inequality Trends and K-S Complementarity

- Hecksher-Olin: as countries open to trade
  1. Skill premium rises in skill-abundant countries and falls in others
  2. Price of skill-intensive goods (e.g., capital equipment) rises
- Data
  1. Skill premium has increased in many poor countries
  2. Relative price of capital has fallen precipitously

Global Inequality Trends and K-S Complementarity

- Parro (AEJ: Macro 2019)
- Embeds capital-skill complementarity in a quantitative model of trade
- Key fact: developing countries import much of their capital equipment
- In poor countries, a reduction in trade costs:
  1. Decreases the price of capital goods imported from the 'North'
  2. Fosters imports of capital goods
  3. Increases the skill premium through capital-skill complementarity

Taking Stock

- KSC is a central insight to interpret inequality dynamics
- Key feature of aggregate production relations with multiple (L, K) inputs
- Also valuable to other areas of macroeconomics, such as
  - Business cycle (Lindquist, RED 2004)
  - Taxation (Brinca, Duarte, Holter, Oliveira, WP 2022)
  - Monetary policy (Dolado, Motiovszki, Pappa AEJ: Macro 2022)

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Thanks!

Definition I: Hicks q-complementarity

- A rise in K_e increases the marginal product (wage) of S more than the marginal product (wage) of U

- True whenever S is a stronger q-complement than U with K_e

$$\varepsilon_{K_e U} = \frac{1}{\text{share}_{K_e}} \cdot \frac{\partial \log F_U}{\partial \log K_e} = 1 - \sigma$$

$$\varepsilon_{K_e S} = \frac{1}{\text{share}_{K_e}} \cdot \frac{\partial \log F_S}{\partial \log K_e} = 1 - \sigma + \frac{1}{\text{share}_X}(\sigma - \rho)$$

$$\varepsilon_{K_e S} > \varepsilon_{K_e U} \quad \Leftrightarrow \quad \sigma > \rho$$

- Note: (K_e, U) are always q-complement $\Rightarrow$ also unskilled wages $\uparrow$

Definition II: Allen p-complementarity

- True whenever

$$\varepsilon_{K_e U} = -\frac{1}{\text{share}_{K_e}} \cdot \frac{\partial \log U}{\partial \log q} = -\frac{1}{1-\sigma}$$

$$\varepsilon_{K_e S} = -\frac{1}{\text{share}_{K_e}} \cdot \frac{\partial \log S}{\partial \log q} = -\frac{1}{1-\sigma} + \frac{1}{\lambda_X}\left(\frac{1}{1-\sigma} - \frac{1}{1-\rho}\right)$$

$$\varepsilon_{K_e S} > \varepsilon_{K_e U} \quad \Leftrightarrow \quad \sigma > \rho$$

- Note: (K_e, U) are always p-substitutes

  (K_e, S) can be p-complement if $\sigma >> \rho$