EC569 Economic Growth
Lecture4

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Economic Growth in the Solow model

What's the long-run growth rate of income per capita in the Solow Model?

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The Extended Solow model

Retain assumptions:

- Constant returns to scale production function: $F(K, ehL)$
- A constant fraction (γ) of output is invested.
- A constant fraction (δ) of physical capital stock depreciates.
- Labor force participation rate is constant.
- Population grows at a constant rate, n.
- Human capital, h, is constant.

Differently, assume

- Labor augmenting productivity, e, grows at a constant rate, g.

$$\frac{\dot{e}}{e} = g \Leftrightarrow e(t) = e_0 e^{gt}$$

Clarification...

- Previously, we assumed production function is $AF(K, hL)$
  - Here, A is Hicks-neutral technology
- In the Extended Solow model, technology needs to be labor-augmenting: $F(K, ehL)$
  - Here, e is labor-augmenting or Harrod-neutral technology
- In Cobb-Douglas production, this distinction is not important.
  - $K^{\alpha}(ehL)^{1-\alpha} = AK^{\alpha}(hL)^{1-\alpha}$, where $A \equiv e^{1-\alpha}$

Accumulation of physical capital

- Change in capital stock = Investment - Depreciation

$$\dot{K} = I - D$$

- A constant fraction, γ, of output is invested

$$I = \gamma Y$$

- A constant fraction, δ, of capital depreciates

$$D = \delta K$$

$$\dot{K} = \gamma Y - \delta K$$

Accumulation of capital-technology ratio

- Goal: write accumulation of capital-technology ratio, $\tilde{k} \equiv \frac{K}{eL}$
- Capital-technology ratio, $\tilde{k}$, sometimes referred as capital per effective labor.
- Why do we need to convert physical capital accumulation equation into capital-technology units?
- Because capital stock will grow as a result of increasing population and higher productivity.

Accumulation of capital-technology ratio, cont'd

- Accumulation of capital

$$\dot{K} = \gamma Y - \delta K$$

- How do we transform $\dot{K}$ into $\dot{\tilde{k}}$?
  - make use of $\tilde{k} \equiv \frac{K}{eL}$
  - take log of $\tilde{k}(t) \equiv \frac{K(t)}{e(t)L(t)}$:

$$\ln(\tilde{k}(t)) = \ln\left(\frac{K(t)}{e(t)L(t)}\right) = \ln(K(t)) - \ln(e(t)) - \ln(L(t))$$

  - Then differentiate with respect to time, t,

$$\frac{\dot{\tilde{k}}(t)}{\tilde{k}(t)} = \frac{\dot{K}(t)}{K(t)} - \frac{\dot{e}(t)}{e(t)} - \frac{\dot{L}(t)}{L(t)}, \qquad \frac{\dot{\tilde{k}}}{k} = \frac{\dot{K}}{K} - g - n$$

  - Remember chain-rule:

$$\frac{df(g(x))}{dx} = \frac{df}{dg}\frac{dg}{dx}$$

Accumulation of capital-technology ratio, cont'd (2)

- Divide each side of $\dot{K} = \gamma Y - \delta K$ by K:

$$\frac{\dot{K}}{K} = \frac{\gamma Y}{K} - \delta$$

- Then,

$$\frac{\dot{\tilde{k}}}{\tilde{k}} + g + n = \frac{\dot{K}}{K} = \frac{\gamma Y}{K} - \delta$$

$$\frac{\dot{\tilde{k}}}{\tilde{k}} + g + n = \frac{\gamma Y/(eL)}{K/(eL)} - \delta$$

$$\frac{\dot{\tilde{k}}}{\tilde{k}} + g + n = \frac{\gamma \tilde{y}}{\tilde{k}} - \delta, \text{ where } \tilde{y} \equiv \frac{Y}{eL}$$

$$\frac{\dot{\tilde{k}}}{\tilde{k}} = \frac{\gamma \tilde{y}}{\tilde{k}} + (\delta + g + n) \quad \Rightarrow \quad \dot{\tilde{k}} = \gamma \tilde{y} - (\delta + g + n)\tilde{k}$$

Steady State

$$\dot{\tilde{k}} = \gamma \tilde{y} - (\delta + g + n)\tilde{k}, \text{ or}$$

$$\dot{\tilde{k}} = \gamma f(\tilde{k}) - (\delta + g + n)\tilde{k}, \text{ where } \tilde{y} = f(\tilde{k}) = F(K, ehL)/(eL)$$

Capital-technology ratio is constant at the steady state.

- if $\gamma f(\tilde{k}) > (\delta + g + n)\tilde{k}$, then $\dot{\tilde{k}} > 0$
- if $\gamma f(\tilde{k}) < (\delta + g + n)\tilde{k}$, then $\dot{\tilde{k}} < 0$
- if $\gamma f(\tilde{k}) = (\delta + g + n)\tilde{k}$, then $\dot{\tilde{k}} = 0$: **steady state**

The Solow Diagram

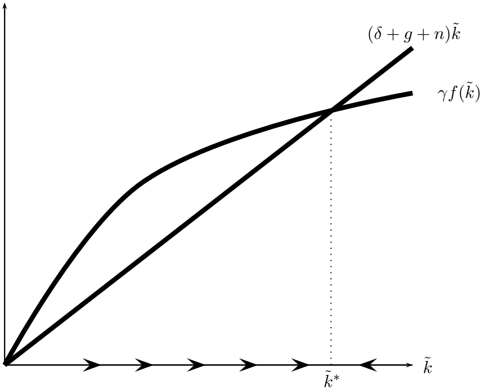


Diagram from Jones and Vollrath (2013)

If $\tilde{k} < \tilde{k}^*$, capital-technology ratio and output-technology ratio will increase.
If $\tilde{k} > \tilde{k}^*$, capital-technology ratio and output-technology ratio will decrease.

Steady State, cont'd

Cobb-Douglas production function

$$Y = K^{\alpha}(ehL)^{1-\alpha}$$

$$\frac{Y}{eL} = \frac{K^{\alpha}(ehL)^{1-\alpha}}{(eL)^{\alpha}(eL)^{1-\alpha}}$$

$$\tilde{y} = \tilde{k}^{\alpha}h^{1-\alpha}$$

No change of capital-technology ratio at the steady state

$$\dot{\tilde{k}} = \gamma\tilde{k}^{\alpha}h^{1-\alpha} - (\delta + g + n)k$$

$$0 = \gamma(\tilde{k}^{*})^{\alpha}h^{1-\alpha} - (\delta + g + n)k^{*}$$

$$\gamma(\tilde{k}^{*})^{\alpha}h^{1-\alpha} = (\delta + g + n)\tilde{k}^{*}$$

$$\tilde{k}^{*} = \left(\frac{\gamma}{\delta + g + n}\right)^{1/(1-\alpha)} h$$

Steady steady output per worker:

$$\tilde{y}^{*} = (\tilde{k}^{*})^{\alpha}h^{1-\alpha} = \left(\frac{\gamma}{\delta + g + n}\right)^{\alpha/(1-\alpha)} h$$

Per worker values

Output per worker:

$$y(t) = e(t)\tilde{y}(t)$$

Capital per worker:

$$k(t) = e(t)\tilde{k}(t)$$

Output per worker at the steady state:

$$y(t) = e(t)\tilde{y}^* = e(t)\left(\frac{\gamma}{\delta + g + n}\right)^{\alpha/(1-\alpha)} h$$

Capital per worker:

$$k(t) = e(t)\tilde{k}^* = e(t)\left(\frac{\gamma}{\delta + g + n}\right)^{1/(1-\alpha)} h$$

Comparative Statics

Capital-technology ratio at the steady state:

$$\tilde{k}^* = \left(\frac{\gamma}{\delta + g + n}\right)^{1/(1-\alpha)} h$$

Output-technology ratio at the steady state:

$$\tilde{y}^* = \left(\frac{\gamma}{\delta + g + n}\right)^{\alpha/(1-\alpha)} h$$

- $\tilde{k}^*$ and $\tilde{y}^*$ are rising with investment rate γ, and human capital h,
- $\tilde{k}^*$ and $\tilde{y}^*$ are declining with depreciation rate, δ, population growth rate, n, and rate of technological progress, g.

Increasing the investment rate

As $\gamma \uparrow$, $\tilde{k}^* = \left(\frac{\gamma}{\delta+g+n}\right)^{1/(1-\alpha)} h \uparrow$, $\tilde{y}^* = \left(\frac{\gamma}{\delta+g+n}\right)^{\alpha/(1-\alpha)} h \uparrow$

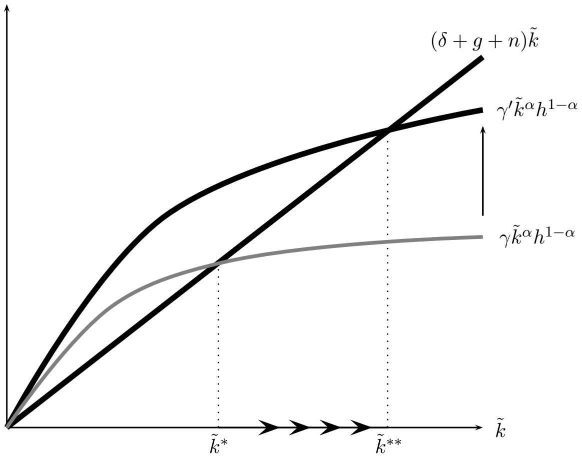


Diagram from Jones and Vollrath (2013)

Output-technology ratio after an increase in investment rate

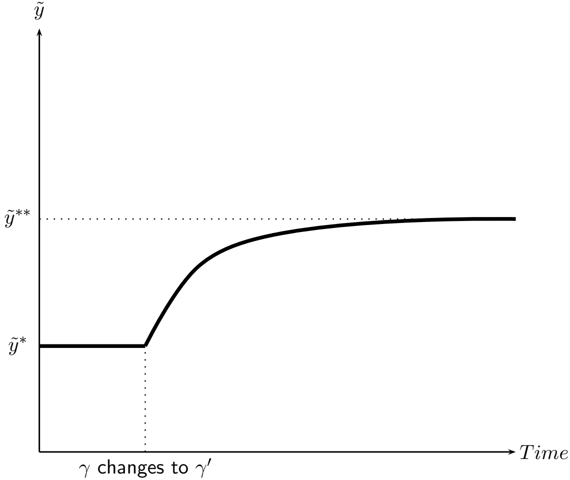


Diagram from Jones and Vollrath (2013)

Output per worker after an increase in investment rate

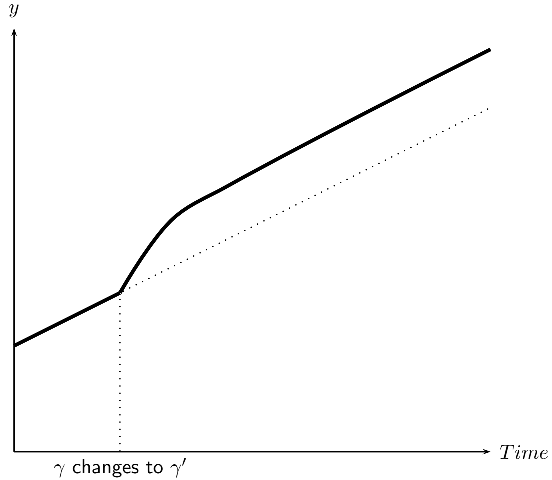


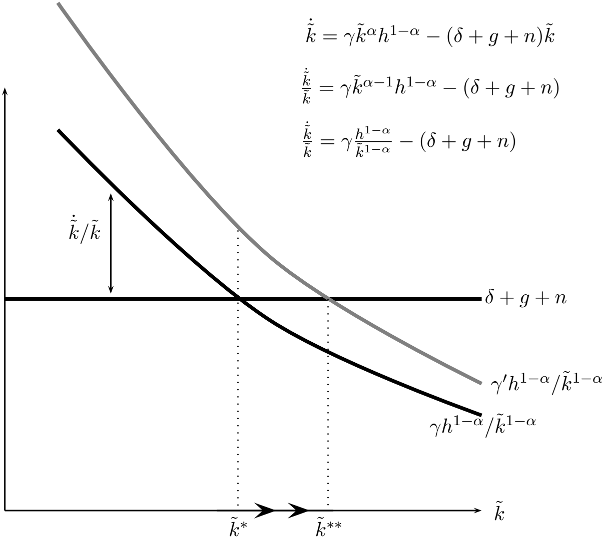
Diagram from Jones and Vollrath (2013)

Growth rate of capital-technology ratio after an increase in investment rate

$$\dot{\tilde{k}} = \gamma \tilde{k}^{\alpha} h^{1-\alpha} - (\delta + g + n)\tilde{k}$$

$$\frac{\dot{\tilde{k}}}{\tilde{k}} = \gamma \tilde{k}^{\alpha-1} h^{1-\alpha} - (\delta + g + n)$$

$$\frac{\dot{\tilde{k}}}{\tilde{k}} = \gamma \frac{h^{1-\alpha}}{\tilde{k}^{1-\alpha}} - (\delta + g + n)$$



Growth rate of output per worker after an increase in investment rate

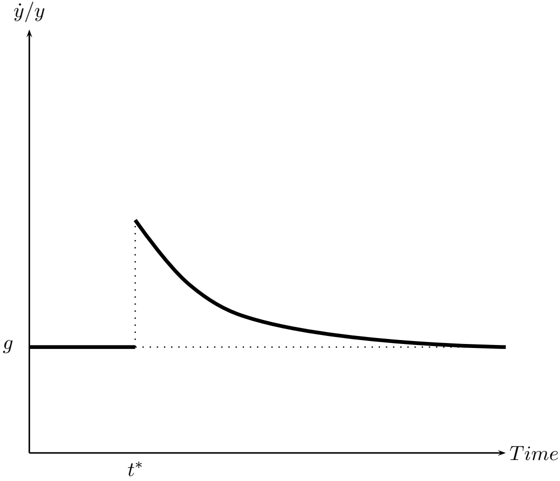


Diagram from Jones and Vollrath (2013)

Exercise

Conduct comparative statics for changes in n, δ, g, and h.

Impact of an increase in investment rate

Short-run:

- Growth rates of capital per worker and income per worker increase.
- Capital per worker and income per worker increases.

Long-run (steady-state):

- Capital per worker and income per worker increases.
- Growth rate of capital per worker and income per worker do not change.

Steady State Growth Rates

	Growth rate at the s.s.
$\tilde{k}$	
$\tilde{y}$	
$\tilde{c}$	
k	
y	
c	
K	
Y	
C	

Steady State Growth Rates

	Growth rate at the s.s.
$\tilde{k}$	0
$\tilde{y}$	0
$\tilde{c}$	0
k	g
y	g
c	g
K	g + n
Y	g + n
C	g + n

Exogenous Growth Model

- Technology is the only source of long-run growth.
- Technology is exogenous: not a results of interactions of agents in the model
- Hence, the extended Solow model is an example of "exogenous growth models."
- It is also referred as "Neo-classical growth model"
- In upcoming lectures, we will analyze "endogenous growth models"
  - Technological progress as a result of actions of model agents.

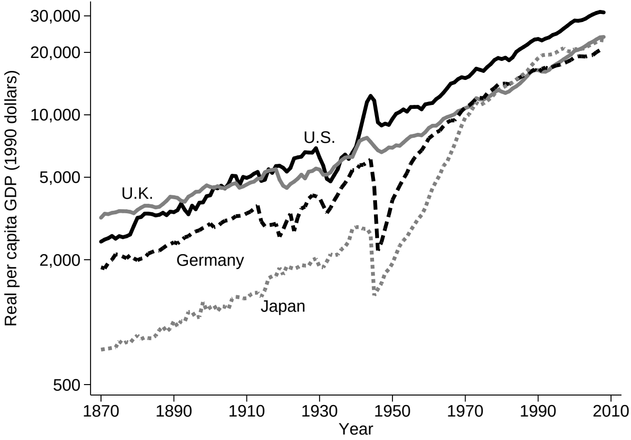
Convergence

Are “poor” countries growing faster than “rich” countries?

Are “poor” countries “closing the gap”?

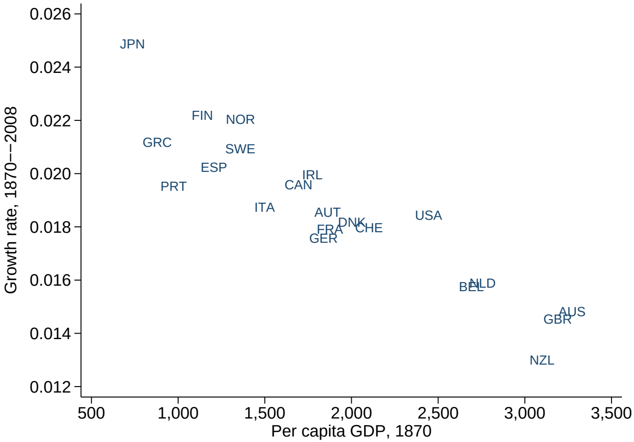
Converge: The phenomenon of “poor” countries catching up with the “rich” countries.

Convergence in a sample of industrialized countries, 1870-2008



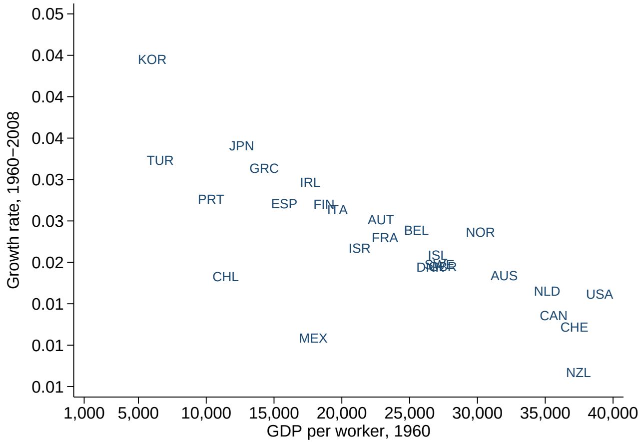
Data source: Maddison (2010)
Graph from: Jones and Vollrath (2013)

Convergence in a sample of industrialized countries, cont'd, 1870-2008



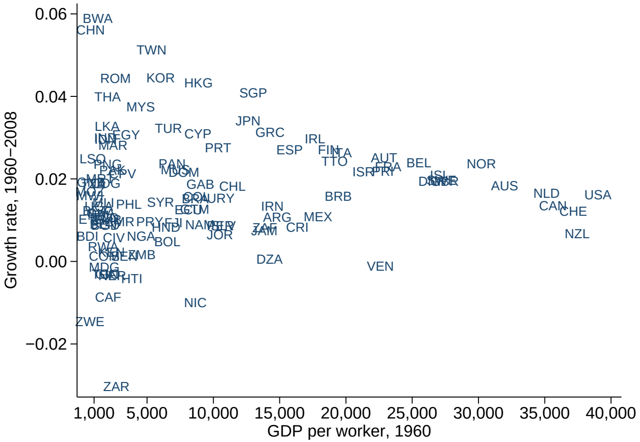
Data source: Maddison (2010)
Graph from: Jones and Vollrath (2013)

Convergence in OECD countries, 1960-2008



Data source: Penn World Tables Mark 7.0 and Summers and Heston (1991)
Graph from: Jones and Vollrath (2013)

The lack of convergence for the World, 1960-2008



Data source: Penn World Tables Mark 7.0 and Summers and Heston (1991)
Graph from: Jones and Vollrath (2013)

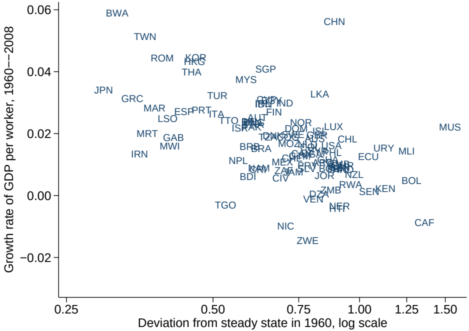
Convergence (?)

- How do we reconcile the converge in OECD but lack of convergence for the world?
- Prediction of the Solow model:
  - Among the countries with the same steady state, poor countries should grow faster than rich countries.
  - Steady state depends on investment rate, population growth rate, technological progress rate
- OECD countries show similarities in investment rate, population growth rate, rate of technological progress.
- More variation in the World in these statistics.

Conditional convergence

- Mankiw, Romer, and Weil (1992), and Barro and Sala-i-Martin (1992):
- Convergence of countries "conditional on" their steady states
- Countries that are poor relative to their steady states tend to grow faster.

"Conditional" convergence for the World, 1960-2008



Data source: Author's calculations using Penn World Tables 7.0, update of Summers and Heston (1991).

Note: The variable on the x-axis is $\hat{y}_{60}/\hat{y}^*$. Estimates of A for 1970 are used to compute the steady state.

Graph from: Jones and Vollrath (2013)

Summary

- We developed a model in which technological progress is the only source of long-run growth
- We looked at the convergence of countries: countries with similar steady states converge but not all countries.

Thank you!