

# Endogenous growth: What matters are new ideas

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Growth Theory

## **Why we need to understand the source of technological progress:**

- Technological growth is the engine of growth in the Solow model.
- Cross-country differences in technology are key to understand output per worker differences.
- Growth miracles result partially from fast technological growth.

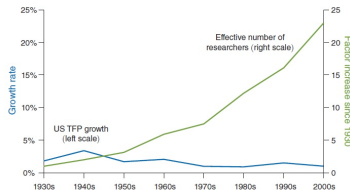
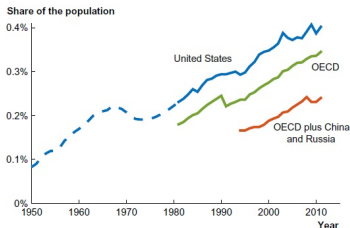
- [Romer \(1990\)](#) presents a framework on how to analyze technological growth through research. For that work, he won the [Nobel price](#).
- The framework is thought to model growth at the technological frontier through discovering new innovations.
- Afterward, we will consider how countries that lack behind may grow by copying existing ideas.

# How ideas are discovered

## How do we discover new ideas? Two competing views:

- Standing on the shoulders of giants: As great innovators before us have come up with great ideas, it becomes easier to develop new ideas. For example, it would have been impossible to travel to the moon, if Newton and Leibniz had not invented calculus. This idea suggests that we will discover ideas faster over time with a constant R&D input.
- The easiest fruits are already picked: Imagine there are a lot of new ideas out there but discovering each contains a varying degree of difficulty. For example, in medicine, doctors washing their hands lead to a drastic decline in mortality, yet discovering new cancer treatments has proven difficult. Naturally, we will begin by discovering easy ideas first. This idea suggests that we will discover ideas slower over time with a constant R&D input.

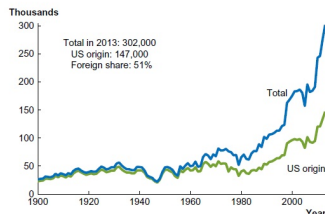
# Increasing R&D input



Source: [Jones \(2016\)](#) and [Bloom et al. \(2020\)](#)

- Over time, the rate of innovation, i.e., technological progress is close to constant.
- However, we have increased the number of inputs, i.e., the number of R&D workers.
- This suggests that we are running out of easy ideas.

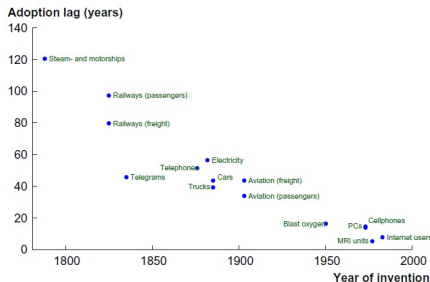
# Falling R&D output productivity



Source: [Jones \(2016\)](#)

- Despite the number of researchers increasing in the U.S. exponentially, the number of new patents is close to flat with the recent increase likely due to regulatory changes.
- More patents to foreigners lead to more granted patents but even that did not increase productivity growth suggesting that innovations become more marginal.

# Speed of adoption



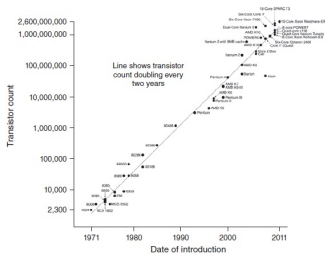
Source: [Jones \(2016\)](#)

- Once a new idea is developed, it still needs to be adopted by the economy.
- The data suggests that today, we are quicker in adopting new ideas than in the past.



- Bloom et al. (2020) look at three cases where they can observe the input and output in the ideas production function.
- This allows them to study changes in research productivity within a field over time.
- They find that research productivity is falling by around 8% per year.

# Moore's law



Source: Bloom et al. (2020)

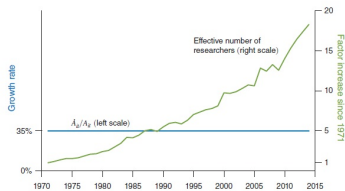
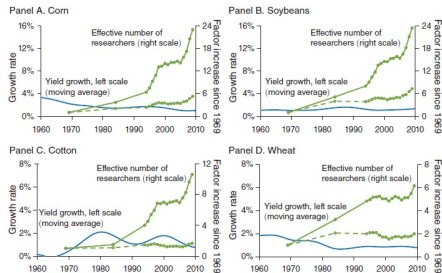


FIGURE 4. DATA ON MOORE'S LAW

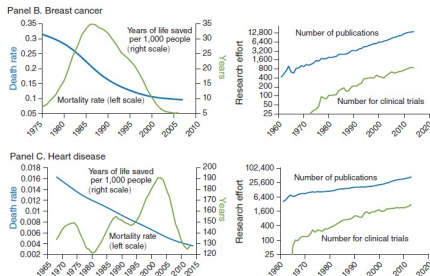
- Since the 1970s, the number of transistors on a CPU doubles every 2 years implying a yearly research output of 35%.
- Using R&D and wage data from the major chip manufacturers, today we need 18 times more input for the same growth than in the 1970s.

# Crop yield



Source: [Bloom et al. \(2020\)](#)

- The increase in crop yields was relatively constant since the 1960s.
- At the same time, the number of researchers trying to increase crop yields has risen sharply.
- The data suggests a 6% yearly productivity decline.



Source: Bloom et al. (2020)

- Improvements in health outcomes show no exponential growth, i.e., constant growth rates.
- However, the number of researchers, again, has increased drastically.

# The model

# Do we need a new framework? Non-rivalrous good

It may be tempting to think about technology as just another input we can accumulate (like capital) and just modify our Solow model. This, however, misses a key aspect of technology: Different from capital, technology is a **non-rivalrous** good. If one person comes up with a better idea of producing, everyone could, in principle, use that idea:

- A newly discovered computer algorithm could be used by all producers/consumers.
- A newly discovered drug could benefit all sick people.
- Just-in-time delivery could be employed by all firms.
- A more efficient airplane design could be used by all firms.

# Do we need a new framework? Increasing returns to scale

Non-rivalry often leads to increasing returns to scale:

- Producing the first unit is expensive as a lot of R&D needs to be invested.
- Once the new idea is discovered, producing more units comes at relatively cheap (sometimes zero) marginal costs. For example:

$$f(x) = 100(x - F). \quad (1)$$

- Hence,  $f(ax) > af(x)$ , i.e., we have increasing returns to scale.

# Do we need a new framework? Imperfect competition

With increasing returns to scale, markets usually give rise to imperfect competition:

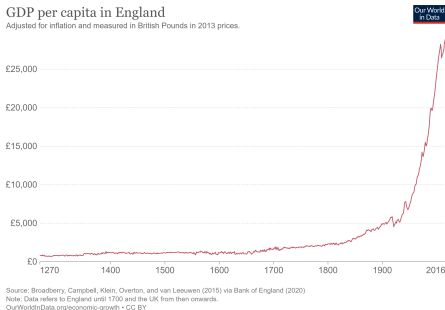
- The average costs are always higher than marginal costs. Hence,  $p = MC$  would result in negative profits and no firms entering the market.
- Instead, imperfectly competitive firms need to make a profit on each unit of production to recuperate the large fixed costs.
- This requires that the good is excludable. Otherwise, the government will have to do the innovations, e.g., innovations in national defense.



# How can firms make profits with their innovations?

- Some new ideas may be hard to copy. For example, the Coca Cola recipe was a trade-secret for a long time. Also firm organization innovations, such as new management styles may be hard to observe and difficult to copy from one firm to another.
- In other cases, e.g., new drugs, reverse engineering and copying may be relatively simple. To give firms and individuals nevertheless an incentive to innovate, the government grants temporary monopolies to innovations:
  - Patents for tangible ideas.
  - Copyrights for non-tangible ideas.

# Can patenting explain the growth take-off?



- Remember that we did not observe growth in output per worker since relatively recently.
- England established a patent law in 1624 but the diffusion was slow.
- Some economists believe that spreading intellectual property protection was a major contributor to the industrial revolution.

# The Romer model

Romer (1990) proposes a model where new ideas add to the existing stock of ideas. Conceptually, it is simplest to have a model with four different sectors:

- The household sector saves and accumulates the aggregate, homogeneous capital stock.
- Researchers develop new product designs taking the form of capital goods, e.g., the design of a new computer.
- An intermediate firm buys this design and uses capital from the household sector to turn it into a productive capital good on which it holds a patent.
- Finally, a large number of final goods producers buy these capital goods and produce the final good under perfect competition.

The household sector, as before, accumulates the aggregate capital stock that will be available to transform into productive capital:

$$\dot{K}(t) = sY(t) - \delta K(t), \quad (2)$$

where  $Y$  is the final output good. Different from before, the household works either in the goods producing sector,  $L_Y$ , or the research sector,  $L_A$ :

$$L(t) = L_Y(t) + L_A(t) \quad (3)$$

$$L_A(t) = s_R L(t). \quad (4)$$

To produce the final output good, we require differentiated capital goods. For example, an economy needs:

- microchips
- robots
- brain scanner
- car chassis designs
- combustion engines

# Final goods production II

The final goods producer use production labor and a measure of  $A(t)$  available capital goods to produce the final output good:

$$Y(t) = L_Y(t)^{1-\alpha} \int_0^{A(t)} x_j(t)^\alpha dj. \quad (5)$$

Note, the function has constant returns to scale with respect to capital and labor. For a given amount of capital goods,  $A$ , doubling  $L_Y$  and each  $x_j$  will double output.

# Optimal input demand

Given the wage,  $w$ , and the prices of each capital good,  $p_j$ , the final goods producer choose the quantity of each capital good and labor to maximize profits (the price of the final output good is 1, and omitting the time indexes):

$$\max_{L_Y, x_j} \left\{ \Pi = L_Y^{1-\alpha} \int_0^A x_j^\alpha dj - wL_Y - \int_0^A p_j x_j dj \right\}. \quad (6)$$

$$\frac{\partial \Pi}{\partial L_Y} = (1 - \alpha) L_Y^{-\alpha} \int_0^A x_j^\alpha dj - w = 0 \quad (7)$$

$$w = (1 - \alpha) \frac{Y}{L_Y}. \quad (8)$$

$$\frac{\partial \Pi}{\partial x_j} = \alpha L_Y^{1-\alpha} x_j^{\alpha-1} - p_j = 0 \quad (9)$$

$$p_j = \alpha L_Y^{1-\alpha} x_j^{\alpha-1}. \quad (10)$$

The capital good producers buy patent designs from researchers at a fixed price  $P_A$ . Once they have the design, they produce capital goods by transforming the capital from the household sector into productive capital goods at a one-to-one rate. The price of capital is  $r$ :

$$\max_{x_j} \{ \pi_j = p_j(x_j)x_j - rx_j \}, \quad (11)$$

where  $p_j(x_j)$  is given by the demand function (10).



$$\frac{\partial \pi_j}{\partial x_j} = \frac{\partial p_j(x_j)}{\partial x_j} x_j + p_j - r = 0 \quad (12)$$

$$0 = \frac{\frac{\partial p_j(x_j)}{\partial x_j} x_j}{p_j} + 1 - \frac{r}{p_j}. \quad (13)$$

From (10) we have

$$\frac{\frac{\partial p_j}{\partial x_j} x_j}{p_j} = \frac{(\alpha - 1) \alpha L_Y^{1-\alpha} x_j^{\alpha-2} x_j}{\alpha L_Y^{1-\alpha} x_j^{\alpha-1}} \quad (14)$$

$$= \alpha - 1. \quad (15)$$

Putting things together:

$$p_j = \frac{1}{\alpha} r > r. \quad (16)$$

Imperfect competition implies that the capital goods producers make a profit on each unit they sell:

$$\pi_j = \frac{1}{\alpha} r x_j - r x_j = x_j r \frac{1 - \alpha}{\alpha}. \quad (17)$$

# The research sector

A single researcher discovers ideas according to

$$\bar{\theta} = \theta A(t)^\phi. \quad (18)$$

More researchers lead to more discoveries so that new ideas are discovered according to

$$\dot{A}(t) = \theta L_A(t)^\lambda A(t)^\phi. \quad (19)$$

- More researchers,  $L_A$ , increases idea discoveries. If  $\lambda < 1$ , there is a stepping on your toes effect, otherwise, there are network effects.
- The current stock of ideas,  $A$ , has an ambivalent effect on new ideas. When  $\phi < 1$ , discovering ideas becomes more difficult over time as argued for in the data.

# The value of a patent

The implied costs for having a patent for one period is its price times the one-period return of an alternative investment:  $rP_A$ . Its one-period benefit is the flow profit plus the change in the value of the patent over that period:

$$rP_A = \pi + \dot{P}_A. \quad (20)$$

One can show that this solves for

$$P_A = \frac{\pi}{r - n}. \quad (21)$$

# The number of researchers

To an individual researcher, the value of being a researcher is  $\bar{\theta}P_A$ . This needs to equal her forgone wages from being a production worker:

$$\bar{\theta}P_A = (1 - \alpha) \frac{Y}{L_Y} \quad (22)$$

in steady state, one can show that this solves for

$$s_R = \frac{1}{1 + \frac{r-n}{\alpha g_A}}. \quad (23)$$

- More efficient technological growth will encourage more researchers.
- A higher savings rate will decrease  $r$  and increase research.
- A higher population growth creates more demand for goods.

# The symmetric outcome

As each capital good  $x_j$  has the same cost and the same benefit, the equilibrium outcome is that all are produced in the same quantity:

$$x_j = x. \quad (24)$$

Capital goods market clearing implies, hence:

$$\int_0^A x_j dj = Ax = K \quad (25)$$

$$x = \frac{K}{A}. \quad (26)$$

# The symmetric outcome II

Plugging the result into our final goods production function gives:

$$Y(t) = L_Y(t)^{1-\alpha} A(t) x(t)^\alpha \quad (27)$$

$$Y(t) = L_Y(t)^{1-\alpha} A(t) \left( \frac{K(t)}{A(t)} \right)^\alpha \quad (28)$$

$$Y(t) = (A(t) L_Y(t))^{1-\alpha} K(t)^\alpha \quad (29)$$

which is our familiar production function. Note, the function has increasing returns to scale with regard to all *three* production factors. Moreover, the reason why more capital goods make the economy more productive is that it allows us to escape diminishing marginal returns.

# The steady state

Rewriting the production function:

$$Y(t)^{1-\alpha} = (A(t)L_Y(t))^{1-\alpha} \left( \frac{K(t)}{Y(t)} \right)^\alpha. \quad (30)$$

One can show again that the capital output ratio is constant in steady state. Hence,

$$\left( \frac{\dot{Y}(t)}{Y(t)} \right)^* = \frac{\dot{A}(t)}{A(t)} + \frac{\dot{L}(t)}{L(t)} = \frac{\dot{A}(t)}{A(t)} + n. \quad (31)$$

Moreover, output per worker grows at the rate of new ideas:  $\frac{\dot{A}(t)}{A(t)}$ .



# The growth rate of new ideas

Recall the idea accumulation equation:

$$\dot{A}(t) = \theta L_A(t)^\lambda A(t)^\phi = \theta (s_R L(t))^\lambda A(t)^\phi. \quad (32)$$

When the current stock of ideas does not affect new idea creation,  $\phi = 1$ , we have

$$\frac{\dot{A}(t)}{A(t)} = \theta (s_R L(t))^\lambda, \quad (33)$$

i.e., for a constant  $L(t)$ , we have exponential growth.

# The growth rate of new ideas II

However, the data heavily suggests that  $\phi < 1$ :

$$\frac{\dot{A}(t)}{A(t)} = \frac{\theta(s_R L(t))^\lambda}{A(t)^{1-\phi}} \quad (34)$$

A higher current level of technology slows down technological progress. This appears to suggest that growth inevitably will slow down over time. However,  $s_R L(t)$  may not be constant. That is, the growth rate may still be constant if the numerator and denominator grow at the same rate, i.e.,

$$(1 - \phi) \frac{\dot{A}(t)}{A(t)} = \lambda \frac{\dot{L}(t)}{L(t)} = \lambda n \quad (35)$$

$$\frac{\dot{A}(t)}{A(t)} = \frac{\lambda n}{1 - \phi}. \quad (36)$$

$$\frac{\dot{A}(t)}{A(t)} = \frac{\lambda n}{1 - \phi}. \quad (37)$$

- Constant technological progress is only possible through population growth (or a growing share of people doing research). More people provide more ideas which increases output, i.e., very different from the Solow model.
- The share of researchers in the population does not affect the growth rate of technology.
- Network effects,  $\lambda$ , and stepping on the shoulders of giants,  $\phi$ , create faster technological progress.

# The steady state

To analyze the steady state, define

$$\tilde{k}(t) = \frac{K(t)}{A(t)(1 - s_R)L(t)} \quad (38)$$

$$\tilde{y}(t) = \frac{Y(t)}{A(t)(1 - s_R)L(t)} = \tilde{k}(t)^\alpha. \quad (39)$$

Rewriting the capital accumulation equation:

$$\dot{K}(t) = sK(t)^\alpha (A(t)(1 - s_R)L(t))^{1-\alpha} - \delta K(t) \quad (40)$$

$$\frac{\dot{K}(t)}{K(t)} = s\tilde{k}(t)^{\alpha-1} - \delta \quad (41)$$

$$\frac{\dot{\tilde{k}}(t)}{\tilde{k}(t)} = s\tilde{k}(t)^{\alpha-1} - (n + g_A + \delta). \quad (42)$$

# The steady state II

Conjecture that  $\tilde{k}$  is constant in steady state:

$$(n + g_A + \delta) = s \left( \tilde{k}^* \right)^{\alpha-1} \quad (43)$$

$$\tilde{k}^* = \left( \frac{s}{n + g_A + \delta} \right)^{\frac{1}{1-\alpha}}. \quad (44)$$

Which is indeed a constant. This implies that in steady state

$$\left( \frac{K(t)}{L(t)} \right)^* = \left( \frac{s}{n + g_A + \delta} \right)^{\frac{1}{1-\alpha}} (1 - s_R) A(t) \quad (45)$$

$$\left( \frac{Y(t)}{L(t)} \right)^* = \left( \frac{s}{n + g_A + \delta} \right)^{\frac{\alpha}{1-\alpha}} (1 - s_R) A(t) \quad (46)$$

# Output per worker and the share of researchers

Note that we can rewrite (19) as

$$g_A = \theta L_A(t)^\lambda A(t)^{\phi-1} \quad (47)$$

$$A(t) = \left( \frac{\theta (s_R L(t))^\lambda}{g_A} \right)^{\frac{1}{1-\phi}} \quad (48)$$

Putting things together, we have in steady state:

$$\left( \frac{Y(t)}{L(t)} \right)^* = \left( \frac{s}{n + g_A + \delta} \right)^{\frac{\alpha}{1-\alpha}} (1 - s_R) \left( \frac{\theta (s_R L(t))^\lambda}{g_A} \right)^{\frac{1}{1-\phi}}. \quad (49)$$

# Output per worker and the share of researchers

$$\left(\frac{Y(t)}{L(t)}\right)^* = \left(\frac{s}{n + g + \delta}\right)^{\frac{\alpha}{1-\alpha}} (1 - s_R) \left(\frac{\theta(s_R L(t))^\lambda}{g_A}\right)^{\frac{1}{1-\phi}}. \quad (50)$$

The share of researchers has an ambivalent effect on output per worker:

- More researchers reduce the pool available to produce goods.
- More researchers lead to a higher stock of ideas and, hence, make those producing goods more productive.

Note, output per worker is *increasing* in the population size.

$$\frac{\dot{A}(t)}{A(t)} = \frac{\theta(s_R L(t))^\lambda}{A(t)^{1-\phi}} \quad (51)$$

Our model suggests two ways to temporarily increase technological progress:

- Increase the share of researchers.
- Increase the efficiency of researchers.

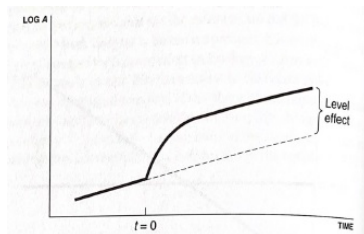


With  $\phi < 1$ , after a one-time increase in either of the two, we have

$$(1 - \phi) \frac{\dot{A}(t)}{A(t)} > \lambda n, \quad (52)$$

i.e., the denominator grows quick than the numerator. As the stock of ideas accumulates,  $\frac{\theta(s_R L(t))^\lambda}{A(t)^{1-\phi}}$  falls and so does the rate of technological progress.

# Transition dynamics III



The temporarily higher growth rate in ideas leads to a permanently higher stock of ideas.

# Transition dynamics for output per worker

As before, let us write output as a function of the capital to output ratio

$$Y(t) = A(t)(1 - s_R)L(t) \left( \frac{K(t)}{Y(t)} \right)^{\frac{\alpha}{1-\alpha}} \quad (53)$$

$$y(t) = A(t)(1 - s_R) \left( \frac{K(t)}{Y(t)} \right)^{\frac{\alpha}{1-\alpha}} \quad (54)$$

$$y(t) = A(t)(1 - s_R)\tilde{k}(t)^\alpha \quad (55)$$

$$\frac{\dot{y}(t)}{y(t)} = \frac{\dot{A}(t)}{A(t)} + \alpha \frac{\dot{\tilde{k}}(t)}{\tilde{k}(t)} \quad (56)$$

with

$$\frac{\dot{\tilde{k}}(t)}{\tilde{k}(t)} = \frac{\dot{K}(t)}{K(t)} - \frac{\dot{A}(t)}{A(t)} - n \quad (57)$$

$$\frac{\dot{\tilde{k}}(t)}{\tilde{k}(t)} = s\tilde{k}(t)^{\alpha-1} - \delta - \frac{\dot{A}(t)}{A(t)} - n \quad (58)$$

# Transition dynamics for output per worker II

$$\frac{\dot{y}(t)}{y(t)} = \frac{\dot{A}(t)}{A(t)} + \alpha \left[ s\tilde{k}(t)^{\alpha-1} - \left( n + \delta + \frac{\dot{A}(t)}{A(t)} \right) \right] \quad (59)$$

Note, in steady state,  $y(t)$  grows at rate  $\frac{\dot{A}(t)}{A(t)}$ . A temporary increase in  $\frac{\dot{A}(t)}{A(t)}$  increases the growth rate of  $y(t)$  but it increases it initially by less than the increase in  $\frac{\dot{A}(t)}{A(t)}$  because the capital to output ratio declines initially.

- In the Romer model, once discovered, designs are used forever.
- However, going back to [Schumpeter](#), economists have thought about technological progress as [better designs replacing older designs](#).
- For example,
  - touchscreen phones replaced keyboard phones.
  - the jet engine replaced propellers.
  - just-in-time delivery replaced large central storage units.
- [Grossman and Helpman \(1991\)](#) and [Aghion and Howitt \(1992\)](#) develop models of this creative destruction.

# The model economy

As before, we will have the same four sectors:

- The household sector saves and accumulates the aggregate, homogeneous capital stock.
- Researchers develop new product designs taking the form of capital goods, e.g., the design of a new computer.
- An intermediate firm buys this design and uses capital from the household sector to turn it into a productive capital good on which it holds a patent.
- Finally, a final goods producer buys these capital goods and produces the final good under perfect competition.

The household sector, as before, accumulates the aggregate capital stock and works in the final good sector or the research sector:

$$\dot{K}(t) = sY(t) - \delta K(t) \quad (60)$$

$$L(t) = L_Y(t) + L_A(t) \quad (61)$$

$$L_A(t) = s_R L(t). \quad (62)$$

The final goods producer use production labor and the latest version of capital,  $x_i$  and productivity  $A_i$  to produce:

$$Y(t) = (L_Y(t)A_i(t))^{1-\alpha} x_i(t)^\alpha, \quad (63)$$

with  $x_i$  being newer and more productive than  $x_{i-1}$ . For example,  $x_i$  may be the jet engine and  $x_{i-1}$  the propeller, and  $A_i$  measures the productivity of the jet engine while  $A_{i-1}$  is the productivity of the propeller.



# Optimal input demand

Given the wage,  $w$ , and the prices of each capital good,  $p_i$ , the final goods producer choose the quantity of each capital good and labor to maximize profits (the price of the final output good is 1, and omitting the time indexes):

$$\Pi = \max_{L_Y, x_i} \left\{ (L_Y A_i)^{1-\alpha} x_i^\alpha - w L_Y - p_i x_i \right\}. \quad (64)$$

$$w = (1 - \alpha) \frac{Y}{L_Y} \quad (65)$$

$$p_i = \alpha (L_Y A_i)^{1-\alpha} x_i^{\alpha-1}. \quad (66)$$

# Capital good producers

The capital good producers buy patent designs from researchers at a fixed price  $P_A$ . Once they have the design, they produce capital goods by transforming the capital from the household sector into productive capital goods at a one-to-one rate. The price of capital is  $r$ :

$$\max_{x_i} \{ \pi_i = p_i(x_i)x_i - rx_i \}, \quad (67)$$

which solves again for

$$p_i = \frac{1}{\alpha} r. \quad (68)$$

As all designs  $i$  charge the same price, the final goods producer will indeed only buy the latest design, and only this capital goods producer will have sales, i.e.,  $x_i = K$ .

# The research sector

Each new innovation is a constant improvement over the last innovation:

$$A_i(t) = (1 + \gamma)A_{i-1}(t). \quad (69)$$

The probability that a researcher finds a new design is

$$\bar{\mu} = \frac{\theta L_A(t)^{\lambda-1}}{A_i(t)^{1-\phi}}. \quad (70)$$

Hence, the probability that a new design is discovered is

$$\bar{\mu}L_A(t) = \frac{\theta L_A(t)^\lambda}{A_i(t)^{1-\phi}}. \quad (71)$$

# The value of a patent

When computing the value of a patent, we have to take into account that it loses all value with probability  $\bar{\mu}L_A$ :

$$rP_A = \pi + \dot{P}_A - \bar{\mu}L_AP_A. \quad (72)$$

One can show that this solves for

$$P_A = \frac{\pi}{r - n + \bar{\mu}L_A(1 - \gamma)}. \quad (73)$$

The more innovative a new patent is,  $\gamma$ , the more value it has. The more likely that a new innovation comes along,  $\bar{\mu}$ , the lower is the value.

# The number of researchers

Using again a non-arbitrage condition, in steady state, one can show that the share of researchers is

$$s_R = \frac{1}{1 + \frac{r - n + \bar{\mu} L_A (1 - \gamma)}{\alpha \bar{\mu} L_A}}. \quad (74)$$

A higher research efficiency makes me more likely to receive a patent and, thus, increasing the number of researchers but it also reduces its value.

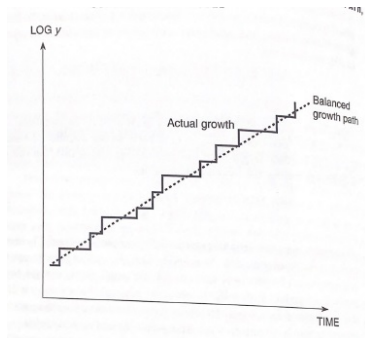
# The aggregate production function

Using the fact that  $x_i = K$ , we have again

$$Y(t) = (A(t)L_Y(t))^{1-\alpha} K(t)^\alpha \quad (75)$$

which is our familiar production function.

# The steady state



- As the arrival of ideas is now stochastic, growth is no longer smooth.
- In expectations, growth rates are the same as in the Romer model.

# Back to our three big questions

- ① Why are we so rich and they so poor?
  - Different saving rates, population growth rates, and technologies for idea accumulation.
- ② Why are there growth miracles?
  - Rapid accumulation of physical capital or ideas.
- ③ What are the engines of long run economic growth?
  - Population growth.



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