

# Macroeconomics

Class 8.

More about Solow model

## Sinking into memories: A general production function in the Solow growth model

- Consider a general production function

$$Y = F(L, K)$$

- This is a “neoclassical” production function if there are positive and diminishing returns to K and L; if there are constant returns to scale (CRS); and if it obeys the Inada conditions:

$$f(0) = 0; f'(0) = \infty; \lim_{k \rightarrow \infty} f'(k) = 0$$

- with CRS, we have output per worker of

$$Y/L = F(1, K/L)$$

If we write  $K/L$  as  $k$  and  $Y/L$  as  $y$ , then in *intensive form*:

$$y = f(k)$$

# Sinking into memories: The Cobb-Douglas production function

- One simple production function that provides – as many economists believe – a reasonable description of actual economies is the ***Cobb-Douglas***:

$$Y = AK^\alpha L^{1-\alpha}$$

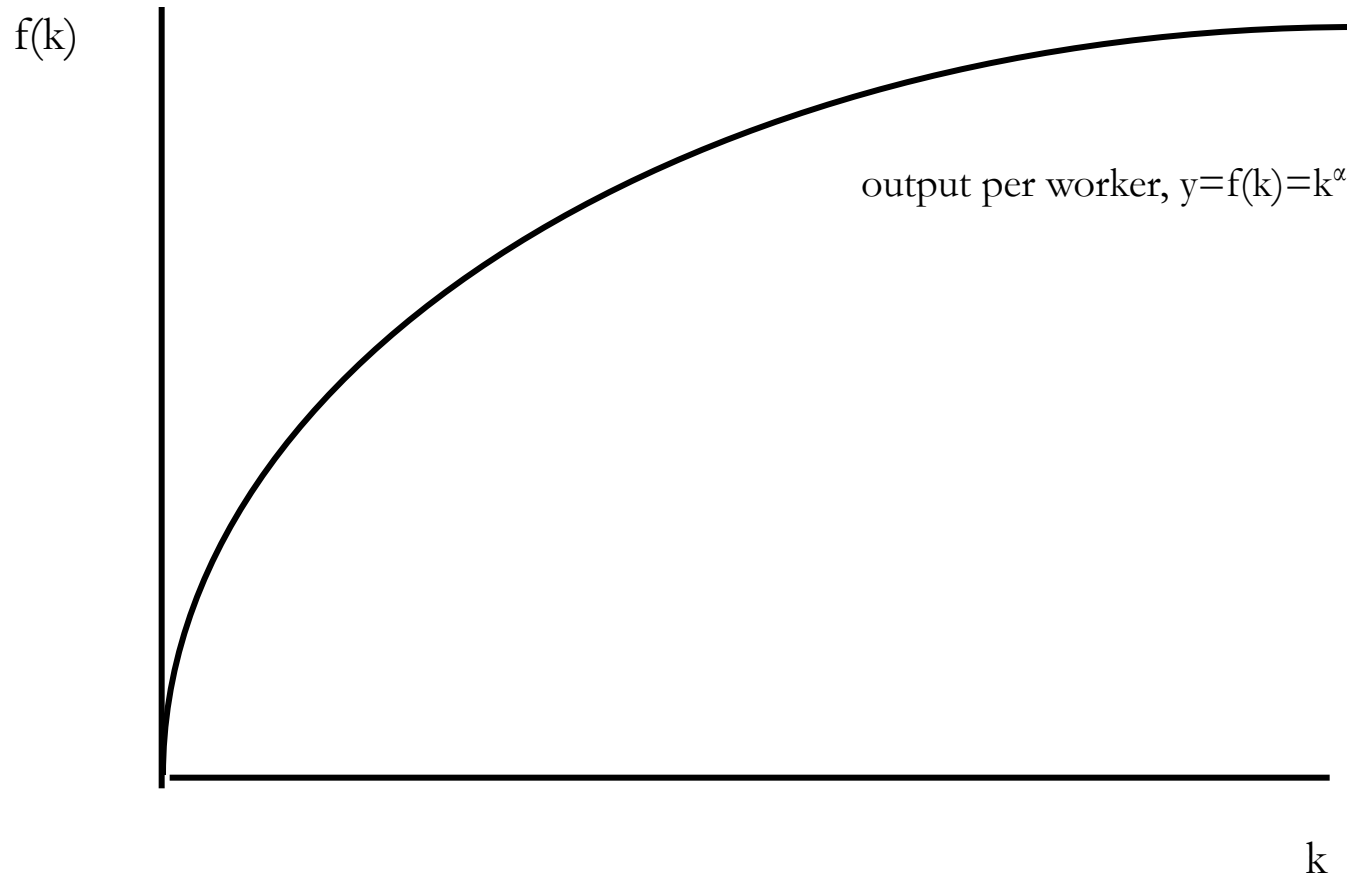
where  $A > 0$  is the level of technology and  $\alpha$  is a constant with  $0 < \alpha < 1$ . The CD production function can be written in *intensive form* as

$$y = Ak^\alpha$$

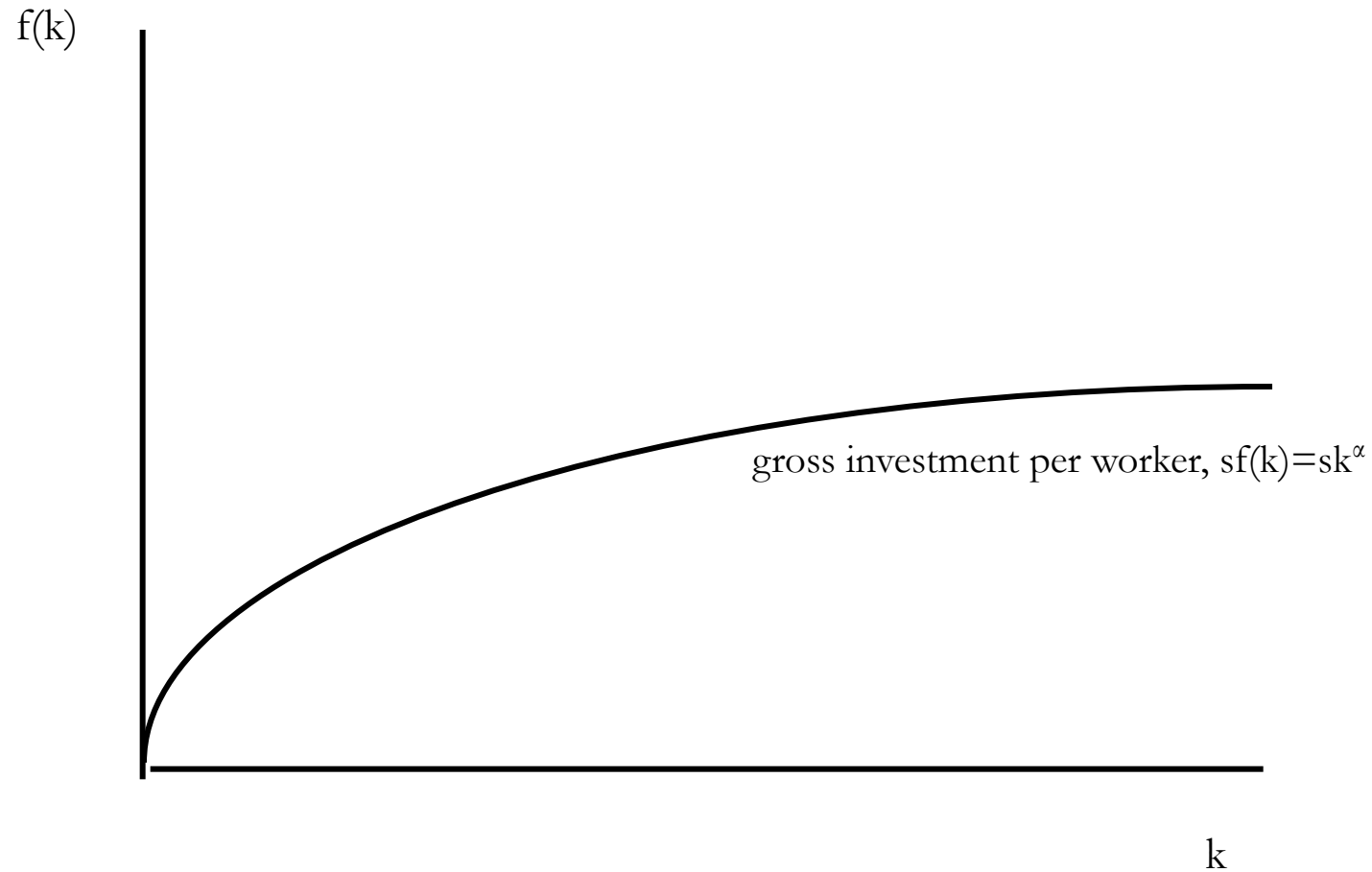
The marginal product can be found from the derivative:

$$\text{MPK} = \frac{\partial Y}{\partial K} = \alpha AK^{\alpha-1} L^{1-\alpha} = \alpha \frac{AK^\alpha L^{1-\alpha}}{K} = \alpha \frac{Y}{K} = \alpha \text{APK}$$

# Sinking into memories: Diminishing returns to capital



Sinking into memories: The economy is saving and investing a constant fraction of income...



Sinking into memories: What is  
“labor-augmenting technical progress”?

- This is technical progress that increases contribution of labor into output!

Sinking into memories: If we take into account “labor-augmenting technical progress” that

- We now write the production function as:

$$Y = F(K, L \times E)$$

- where  $L \times E$  = the number of effective workers.
  - Hence, increases in labor efficiency have the same effect on output as increases in the labor force.

# Sinking into memories: Production function with technical progress in the intensive form

- Notation:

$y = Y/LE$  = output per effective worker

$k = K/LE$  = capital per effective worker

- Production function per effective worker:

$$y = f(k)$$

- Saving and investment per effective worker:

$$s y = s f(k)$$



# Sinking into memories: What is break-even investment?

$(\delta + n + g)k$  = break-even investment:  
the amount of investment necessary  
to keep  $k$  constant.

Consists of:

$\delta k$  to replace depreciating capital

$n k$  to provide capital for new workers

$g k$  to provide capital for the new  
"effective" workers created by  
technological progress

# Sinking into memories: Derivation of equilibrium capital per effective worker

$$\because \Delta K \text{ (net investment)} = I \text{ (gross investment)} - \delta \cdot K \text{ (depreciation)}$$

$$\Rightarrow \frac{\Delta K}{L \cdot E} = \frac{I}{L \cdot E} - \frac{\delta K}{L \cdot E} \equiv i - \delta \cdot k = s \cdot f(k) - \delta \cdot k$$

$$\text{Since } \Delta k = \Delta\left(\frac{K}{L \cdot E}\right) = \frac{(L \cdot E)\Delta K - K(L \cdot \Delta E + E \cdot \Delta L)}{(L \cdot E)^2}$$

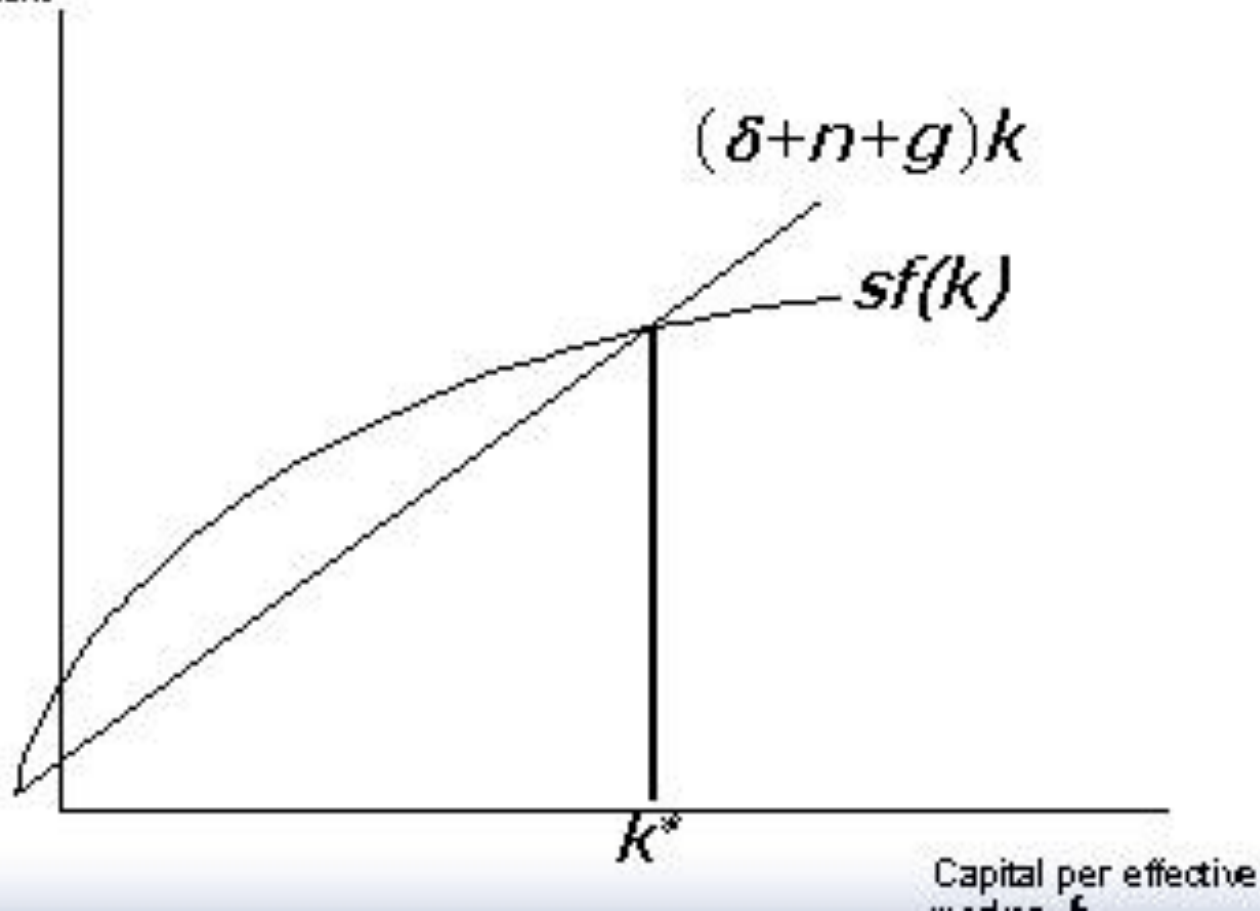
$$= \frac{\Delta K}{L \cdot E} - \frac{K}{L \cdot E} \left(\frac{\Delta L}{L} + \frac{\Delta E}{E}\right)$$

$$= s \cdot f(k) - \delta \cdot k - k(n + g), \text{ where } \frac{\Delta L}{L} \equiv n, \text{ and } \frac{\Delta E}{E} \equiv g$$

$$\Rightarrow \Delta k = s \cdot f(k) - (\delta + n + g)k$$

# Sinking into memories: Equilibrium as a situation of steady-state growth

Investment, break-even:  $\Delta k = s f(k) - (\delta + n + g)k$   
investment



# Sinking into memories: Dynamics of parameters on the steady-state

<b>variable</b>	<b>symbol</b>	<b>Steady-state growth rate</b>
Capital per effective worker	$k = K/(L \times E)$	0
Output per effective worker	$y = Y/(L \times E)$	0
Capital per worker	$(K/L) = k \times E$	$g$
Output per worker	$(Y/L) = y \times E$	$g$
Total output	$Y = y \times E \times L$	$n + g$

# Sinking into memories: Balanced growth

Solow model's steady state exhibits **balanced growth** - many variables grow at the same rate.

- Solow model predicts  $Y/L$  and  $K/L$  grow at same rate ( $g$ ), so that  $K/Y$  should be constant. This is true in the real world.
- Solow model predicts real wage grows at same rate as  $Y/L$ , while real rental price is constant. Also true in the real world.

## Sinking into memories: Growth in steady state and outside steady state

- ***In the steady state*** – when actual investment per “effective worker” = break-even investment - ***the rate of economic growth will be equal to the sum of rate of population growth and rate of technical progress =  $n+g$ .***
- If “initial” capital stock is less than steady state capital stock, then the rate of economic growth will be more than  $n+g$ .

# Sinking into memories: Unconditional convergence

- Solow model predicts that, other things equal, “poor” countries (with lower  $Y/L$  and  $K/L$ ) should grow faster than “rich” ones.
  - If true, then the income gap between rich & poor countries would shrink over time, and living standards “converge.”
  - In real world, many poor countries do NOT grow faster than rich ones. Does this mean the Solow model fails?
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# Sinking into memories: Conditional convergence

- No, because "other things" aren't equal.
  - In samples of countries with similar savings & pop. growth rates, income gaps shrink about 2%/year.
  - In larger samples, if one controls for differences in saving, population growth, and human capital, incomes converge by about 2%/year.
- What the Solow model *really* predicts is **conditional convergence** - countries converge to their own steady states, which are determined by saving, population growth, and education. And this prediction comes true in the real world.



# Sinking into memories: The concept of the Golden Rule

To find the Golden Rule capital stock, express  $c^*$  in terms of  $k^*$ :

$$\begin{aligned}c^* &= y^* - i^* \\ &= f(k^*) - (\delta + n + g)k^*\end{aligned}$$

$c^*$  is maximized when

$$\text{MPK} = \delta + n + g$$

or equivalently,

$$\text{MPK} - \delta = n + g$$

In the Golden Rule Steady State, the marginal product of capital net of depreciation equals the pop. growth rate plus the rate of tech progress.

# Sinking into memories: The Golden Rule – for what?

- Use the Golden Rule to determine whether our saving rate and capital stock are too high, too low, or about right.
- To do this, we need to compare  $(MPK - \delta)$  to  $(n + g)$ .
- If  $(MPK - \delta) > (n + g)$ , then we are below the Golden Rule steady state and should increase  $s$ .
- If  $(MPK - \delta) < (n + g)$ , then we are above the Golden Rule steady state and should reduce  $s$ .

# Sinking into memories: Accounting of growth in Solow model (Part 1)

- **Production Function (CRTS)**

$$Y = F(K, L)$$

- **Increases in Capital and Labor**

$$\Delta Y = (MPK \times \Delta K) + (MPL \times \Delta L)$$

$$\Rightarrow \frac{\Delta Y}{Y} = \alpha \frac{\Delta K}{K} + (1 - \alpha) \frac{\Delta L}{L}$$

where  $\alpha$  is capital's share and  $(1 - \alpha)$  is labor's share.

# Sinking into memories: Accounting of growth in Solow model (Part 2)

- Production Function with Technology

$$Y = AF(K, L)$$

- Technological Progress

$$\frac{\Delta Y}{Y} = \alpha \frac{\Delta K}{K} + (1 - \alpha) \frac{\Delta L}{L} + \frac{\Delta A}{A}$$

Growth in output = Contribution of capital + Contribution of labor + Growth in Total Factor Productivity

The above is the **growth-accounting equation**.

# Sinking into memories: Accounting of growth in Solow model (Part 3)

## ■ Solow Residual

$$\frac{\Delta A}{A} = \frac{\Delta Y}{Y} - \alpha \frac{\Delta K}{K} - (1 - \alpha) \frac{\Delta L}{L}$$

- $\Delta A/A$  is the change in output that cannot be explained by changes in inputs. Thus, the growth in total factor productivity is computed as a residual – that is, as the amount of output growth that remains after we have accounted for the determinants of growth that we can measure. Indeed,  $\Delta A/A$  is sometimes called the *Solow residual*, after Robert Solow, who first showed how to compute it.

# Accounting of growth in the U.S. economy

## In the end of the XX century

(average percentage, % increase per year) Years	SOURCE OF GROWTH			
	Output Growth $\Delta Y / Y$	Capital $\alpha \Delta K / K$	Labor $(1 - \alpha) \Delta L / L$	Total Factor Productivity $\Delta A / A$
1950-1960	3.5	1.1	0.8	1.6
1960-1970	4.1	1.2	1.3	1.7
1970-1980	3.1	0.9	1.6	0.5
1980-1990	2.9	0.8	1.3	0.8
1990-1996	2.2	0.6	0.8	0.8
1950-1996	3.2	0.9	1.2	1.1

# Accounting of growth among “Asian Tigers” In the end of the XX century

%	Hong Kong (1966-1991)	Singapore (1966-1990)	South Korea (1966-1990)	Taiwan (1966-1990)
GDP per capita growth	5.7	6.8	6.8	6.7
TFP* growth	2.3	0.2	1.7	2.6
Δ% labor force participation	38→49	27→51	27→36	28→37
Δ% secondary education or higher	27.2→71.4	15.8→66.3	26.5→75.0	25.8→67.6

\*TFP: total factor productivity

Source: Alwyn Young, “The Tyranny of Numbers: Confronting the Statistical Realities of the East Asian Growth Experience,” *Quarterly Journal of Economics*, August 1995.

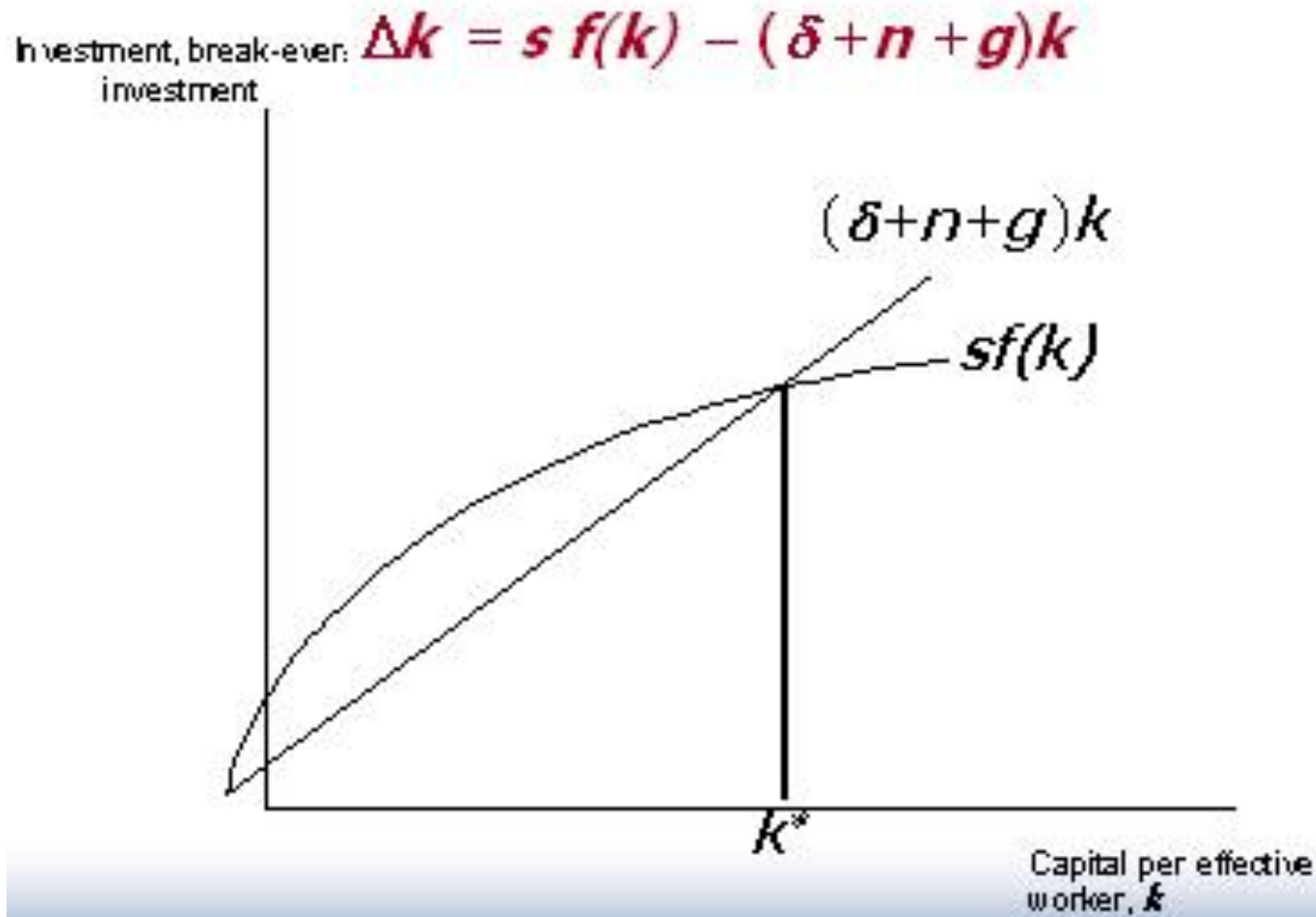
# Exercise #1: the condition

The savings rate = 0.3; the rate of population growth = 0.03; the rate of technical progress = 0.02; the depreciation rate = 0.1. The production function is the Cobb-Douglas function with labor-augmenting technical progress, that is:  $Y = K^{0.5}(LE)^{0.5}$

**Calculate:** Calculate equilibrium capital per effective worker ratio, amount of actual investment and amount of actual consumption.



# Exercise #1: the solution: the graph



# Exercise #1: the solution: the figures

1) If  $Y = K^{0.5}(LE)^{0.5}$

Then  $y = k^{0.5}$

2)  $sy = sk^{0.5} = (n + g + d)k$

$0.3k^{0.5} = (0.03 + 0.02 + 0.1)k$

$0.3k^{0.5} = 0.15k ; 2k^{0.5} = k$

$k = 4 ; y = 2$

3) actual investment = savings =  $s*y = 0.3*2 = 0.6$ .

4) actual consumption =  $y - s = 2 - 0.6 = 1.4$ .

## Exercise #2: the condition

The rate of population growth = 0.04; the rate of technical progress = 0.06; the depreciation rate = 0.08, capital per effective worker ratio = 4. The production function is the Cobb-Douglas function with labor-augmenting technical progress, that is:  $Y = K^{0.5}(LE)^{0.5}$

**Calculate: Calculate equilibrium savings rate, amount of actual investment and amount of actual consumption**

## Exercise #2: the solution:

1) If  $Y = K^{0.5}(LE)^{0.5}$

Then  $y = k^{0.5}$

2)  $sy = sk^{0.5} = (n + g + d)k$

$s * 4^{0.5} = (0.04 + 0.06 + 0.08) * 4$

$s = 0.18 * 4 : 2 = 0.36 = 36\%$

3) actual investment = savings =  $s * y = 0.36 * 2 = 0.72$ .

4) actual consumption =  $y - s = 2 - 0.72 = 1.28$ .

# Exercise #2: the additional question

Is this saving rate – 36% - consistent with the golden rule?

## Exercise #2: reply to the additional question

$$\text{Max } c = (1 - s)y$$

...

If we take  $\partial c / \partial s$  and make it equal to zero that it implies that  $s = \alpha$  or  $s = 0.5$

## Exercise #3: the condition

The savings rate = 0.48; the rate of population growth = 0.04; the rate of technical progress = 0.03; the depreciation rate = 0.05. The production function is the Cobb-Douglas function with labor-augmenting technical progress, that is:  $Y = K^{0.5}(LE)^{0.5}$

**Calculate: Calculate equilibrium capital per effective worker ratio, amount of actual investment and amount of actual consumption.**

## Exercise #4: the condition

The rate of population growth = 0.03; the rate of technical progress = 0.02; the depreciation rate = 0.07, capital per effective worker ratio = 36. The production function is the Cobb-Douglas function with labor-augmenting technical progress, that is:  $Y = K^{0.5}(LE)^{0.5}$

**Calculate: Calculate equilibrium savings rate, amount of actual investment and amount of actual consumption**



## Exercise #5: the condition

**The production function is:  $Y = AK^{0.4}L^{0.6}$**

**The rate of economic growth = 3.9%, the rate of capital accumulation = 3%, the rate of population growth = 2%.**

**Calculate Solow residual**