

Macro 2 Pset 1

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1 Question 1

Show that Equation (8) implies Equation (5).

1.1 Solution

Note that Equation (8) from Lecture 0 is:

$$V(k) = \max_{c, k'} u(c) + \beta V(k')$$

subject to

$$c + k' \leq f(k) + (1 - \delta)k$$

Consider the Lagrangian for this equation:

$$\mathcal{L} = u(c) + \beta V(k_+) + \lambda(f(k) + (1 - \delta)k - c - k_+)$$

Now, we take the FOCs:

$$\frac{\partial \mathcal{L}}{\partial c} = u'(c) - \lambda = 0 \quad (1)$$

$$\frac{\partial \mathcal{L}}{\partial k_+} = \beta V'(k_+) - \lambda = 0 \quad (2)$$

The envelope condition¹ is:

$$V'(k) = \frac{\partial \mathcal{L}}{\partial k} = \lambda f'(k) + \lambda(1 - \delta) = \lambda[f'(k) + (1 - \delta)]$$

From (1) and (2), we have:

$$\lambda = u'(c) = \beta V'(k_+) \quad (3)$$

Applying them to one period earlier gives:

$$\lambda = u'(c_-) = \beta V'(k) \quad (4)$$

Now, use (3) and (4) to replace λ and $V'(k)$ in the envelope condition:

$$\begin{aligned} \frac{u'(c_-)}{\beta} &= u'(c)(f'(k) + (1 - \delta)) \\ \Leftrightarrow u'(c_-) &= \beta u'(c)(f'(k) + (1 - \delta)) \end{aligned}$$

By re-arranging terms and moving our time indicators up by 2 periods, this gives:

$$u'(c_t) = \beta[1 + f'(k_{t+1}) - \delta]u'(c_{t+1})$$

which is Equation (5).

¹Notes on Envelope Theorem; Wikipedia Page on Envelope Theorem

2 Question 2

Show that Equation (14) implies Equation (13).

2.1 Solution

Equation (14) from Lecture 0 is:

$$\rho V(k) = \max_c u(c) + V'(k)[f(k) - c - \delta k] \quad (5)$$

with

$$\dot{k} = f(k) - \delta k - c \quad (6)$$

Consider the FOC of (5) wrt c :

$$u'(c(t)) - V'(k(t)) = 0 \Leftrightarrow u'(c(t)) = V'(k(t)) \quad (7)$$

Additionally, note that

$$u''(c(t))\dot{c}(t) = V''(k(t))\dot{k}(t) \quad \text{Differentiating (7) wrt } t \quad (8)$$

Now, consider the envelope condition for (5):

$$\begin{aligned} \rho V'(k(t)) &= V''(k(t))[f(k(t)) - c(t) - \delta k(t)] + V'(k(t))[f'(k(t)) - \delta] \\ \Leftrightarrow \rho V'(k(t)) &= V''(k(t))\dot{k}(t) + V'(k(t))[f'(k(t)) - \delta] && \text{Substituting in (6)} \\ \Leftrightarrow \rho u'(c(t)) &= V''(k(t))\dot{k}(t) + u'(c(t))[f'(k(t)) - \delta] && \text{Substituting in (7)} \\ \Leftrightarrow \rho u'(c(t)) &= u''(c(t))\dot{c}(t) + u'(c(t))[f'(k(t)) - \delta] && \text{Substituting in (8)} \\ \Leftrightarrow \frac{\dot{c}(t)}{c(t)} &= -\frac{u'(c(t))}{u''(c(t))c(t)}[f'(k(t)) - \rho - \delta] && \text{Rearranging} \end{aligned}$$

Thus, we have Equation (13) from Lecture 0.

3 Question 3

(a) Prove that competitive equilibrium in the economy defined above is efficient (i.e., that competitive equilibrium allocation solves social planner's problem). What are the equilibrium dividends in this economy?

(b) Let $\{c_t^*, k_t^*\}_t$ be the solution to the social planner problem. Use these allocations to construct competitive equilibrium prices $\{r_t^{ce}, R_t^{ce}, w_t^{ce}\}_t$.

Hint (listed beside exercise in notes, not in pset): Remember that for any constant return function $G(x_1, \dots, x_n)$ we have $G(x_1, \dots, x_n) = \sum_{i=1}^n G_i x_i$ where G_i is the partial derivative of $G(x_1, \dots, x_n)$ wrt x_i .

3.1 Part A Solution

As our premise, recall several components of building a competitive equilibrium.

First the household/consumer problem:

$$\max_{\{c_t^{ce}, k_{t+1}^{ce}, b_{t+1}^{ce}\}_t} \sum_{t=0}^{\infty} \beta^t u(c_t^{ce})$$

s.t.

$$c_t^{ce} + k_{t+1}^{ce} + b_{t+1}^{ce} \leq w_t^{ce} + R_t^{ce} b_t^{ce} + r_t^{ce} k_t^{ce} + (1 - \delta) k_t^{ce} + d_t^{ce} \quad \forall t \quad (9)$$

b_{t+1} is bounded below

where $c_t^{ce} \geq 0$, $k_{t+1}^{ce} \geq 0$, k_0 is given, $b_0 = 0$, and, from the household's perspective, w_t^{ce} , R_t^{ce} , r_t^{ce} , and d_t^{ce} are given.

Next, the firm problem:

$$d_t = \max_{\hat{k}_t^{ce}, \hat{l}_t^{ce}} F(\hat{k}_t^{ce}, \hat{l}_t^{ce}) - w_t^{ce} \hat{l}_t^{ce} - r_t^{ce} \hat{k}_t^{ce} \quad (10)$$

Then, our competitive equilibrium can be characterized as the sequence of prices, $\{r_t^{ce}, R_t^{ce}, w_t^{ce}\}_t$, and allocations, $\{c_t^{ce}, k_t^{ce}, b_t^{ce}, d_t^{ce}, \hat{k}_t^{ce}, \hat{l}_t^{ce}\}_t$, such that:

1. $\{c_t^{ce}, k_t^{ce}, b_t^{ce}\}_t$ solves the household problem, taking $\{r_t^{ce}, R_t^{ce}, w_t^{ce}, d_t^{ce}\}_t$ as given.
2. $\{d_t^{ce}, \hat{k}_t^{ce}, \hat{l}_t^{ce}\}_t$ solves the firm problem, taking $\{r_t^{ce}, w_t^{ce}\}_t$ as given.
3. All markets clear, i.e., $k_t^{ce} = \hat{k}_t^{ce}$, $l_t^{ce} = \hat{l}_t^{ce}$, and $b_t^{ce} = 0 \quad \forall t$.

We will begin by looking at the Lagrangian for the household problem. Note that the budget constraint holds with equality, given strictly increasing utility.

$$\mathcal{L} = \sum_{t=0}^{\infty} [\beta^t u(c_t^{ce}) + \lambda_t [w_t^{ce} + R_t^{ce} b_t^{ce} + r_t^{ce} k_t^{ce} + (1 - \delta)k_t^{ce} + d_t^{ce} - c_t^{ce} - k_{t+1}^{ce} - b_{t+1}^{ce}]]$$

The FOCs are then:

$$\frac{\partial \mathcal{L}}{\partial c_t^{ce}} = \beta^t u'(c_t^{ce}) - \lambda_t = 0 \quad \Rightarrow \beta^t u'(c_t^{ce}) = \lambda_t \quad (11)$$

$$\frac{\partial \mathcal{L}}{\partial k_{t+1}^{ce}} = -\lambda_t + \lambda_{t+1} [r_{t+1}^{ce} + (1 - \delta)] = 0 \quad \Rightarrow \lambda_t = \lambda_{t+1} [r_{t+1}^{ce} + (1 - \delta)] \quad (12)$$

$$\frac{\partial \mathcal{L}}{\partial b_{t+1}^{ce}} = -\lambda_t + \lambda_{t+1} R_{t+1}^{ce} = 0 \quad \Rightarrow \lambda_t = \lambda_{t+1} R_{t+1}^{ce} \quad (13)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_t} = 0 \quad \Rightarrow w_t^{ce} + R_t^{ce} b_t^{ce} + r_t^{ce} k_t^{ce} + (1 - \delta)k_t^{ce} + d_t^{ce} - c_t^{ce} - k_{t+1}^{ce} - b_{t+1}^{ce} = 0$$

and the transversality conditions are:

$$\begin{aligned} \lim_{T \rightarrow \infty} \beta^T u'(c_T) l_{T+1} &\leq 0 \\ \lim_{T \rightarrow \infty} \beta^T u'(c_T) b_{T+1} &\leq 0 \end{aligned}$$

Note that from (12) and (13), we have:

$$\begin{aligned} \lambda_t &= \lambda_{t+1} [r_{t+1}^{ce} + (1 - \delta)] = \lambda_{t+1} R_{t+1}^{ce} \\ &\Rightarrow R_{t+1}^{ce} = r_{t+1}^{ce} + (1 - \delta) \end{aligned} \quad (14)$$

Moreover, consider that

$$\begin{aligned} \lambda_t &= \beta^t u'(c_t^{ce}) && \text{by (11)} \\ \lambda_{t+1} &= \beta^{t+1} u'(c_{t+1}^{ce}) && \text{by (11)} \end{aligned}$$

Then

$$\frac{\lambda_{t+1}}{\lambda_t} = \frac{\beta^{t+1} u'(c_{t+1}^{ce})}{\beta^t u'(c_t^{ce})} = \beta \frac{u'(c_{t+1}^{ce})}{u'(c_t^{ce})}$$

Additionally,

$$\frac{\lambda_{t+1}}{\lambda_t} = \frac{\lambda_{t+1}}{\lambda_{t+1} R_{t+1}^{ce}} \quad \text{by (13)}$$

$$\begin{aligned} &= \frac{1}{R_{t+1}^{ce}} \\ &= \frac{1}{r_{t+1}^{ce} + (1 - \delta)} \quad \text{by (14)} \end{aligned}$$

Then,

$$\begin{aligned} \frac{1}{r_{t+1}^{ce} + (1 - \delta)} &= \beta \frac{u'(c_{t+1}^{ce})}{u'(c_t^{ce})} \\ \Rightarrow u'(c_t) &= \beta u'(c_{t+1}) [r_{t+1}^{ce} + (1 - \delta)] \end{aligned} \quad (15)$$

which reflects our standard Euler equation.

Now, we return to the firm's problem in (10).

We have assumed the F is continuous and differentiable and corresponds to positive, diminishing marginal product, and constant returns to scale in l and k . Thus, we have that our problem is concave.

Moreover, we have assumed the existence of a representative firm, taking all firms to make identical decisions and maximize dividends paid to their owners.

Then, our FOCS yield:

$$\begin{aligned} F_k(\hat{k}_t^{ce}, \hat{l}_t^{ce}) &= r_t^{ce} \\ F_l(\hat{k}_t^{ce}, \hat{l}_t^{ce}) &= w_t^{ce} \end{aligned}$$

Then, by properties of CRS functions, we have

$$\begin{aligned} F(\hat{k}_t^{ce}, \hat{l}_t^{ce}) &= \hat{k}_t^{ce} F_k(\hat{k}_t^{ce}, \hat{l}_t^{ce}) + \hat{l}_t^{ce} F_l(\hat{k}_t^{ce}, \hat{l}_t^{ce}) \\ &= \hat{k}_t^{ce} r_t^{ce} + \hat{l}_t^{ce} w_t^{ce} \end{aligned}$$

From this, we have $d_t = 0$, which is logical, since positive dividends would imply that firms should demand arbitrarily large amounts of capital and labor.

Finally, we return to the market clearing conditions and enforce

$$\begin{aligned}k_t^{ce} &= \hat{k}_t^{ce} = k^* \\1 &= l_t^{ce} = \hat{l}_t^{ce} = l^* \\b_t &= 0\end{aligned}$$

Again by CRS properties, we have

$$r_t = f'(k_t)$$

where k reflects the capital-labor ratio. This implies that $r_{t+1} = f'(k_{t+1})$. If we then plug this into our Euler equation, (15), we get:

$$u'(c_t) = \beta u'(c_{t+1})[f'(k_{t+1}) + (1 - \delta)]$$

If we then enforce equality and substitute $f(k_t^*) = r_t^{*ce} k_t^* + w_t^{*ce}$, $d_t = 0$, and $b_t^* = b_{t+1}^* = 0$ into our household budget constraint, (9), we get:

$$c_t^* + k_{t+1}^* = f(k_t^*) + (1 - \delta)k_t^*$$

Recall that the social planner's problem is:

$$\max_{\{c_t, k_t\}} \sum_{t=0}^{\infty} \beta^t u(c_t)$$

s.t.

$$c_t + k_{t+1} \leq f(k_t) + (1 - \delta)k_t \quad \forall t$$

or, via the Lagrangian,

$$\max_{\{c_t, k_t\}} \sum_{t=0}^{\infty} \beta^t u(c_t) + \sum_{t=0}^{\infty} \lambda_t [f(k_t) + (1 - \delta)k_t - c_t - k_{t+1}]$$

which, via the FOCs, yields:

$$u'(c_t) = \beta u'(c_{t+1})[f'(k_{t+1}) + (1 - \delta)]$$

Thus, the two maximization problems are the same, and, assuming based on the phrasing the of the question that the social planner's solution is taken to be efficient, the result of the competitive equilibrium is efficient.

3.2 Part B Solution