Limitation of RBC models

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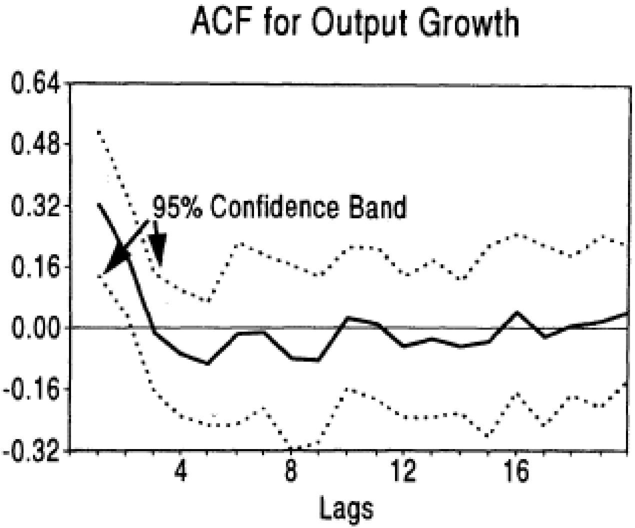
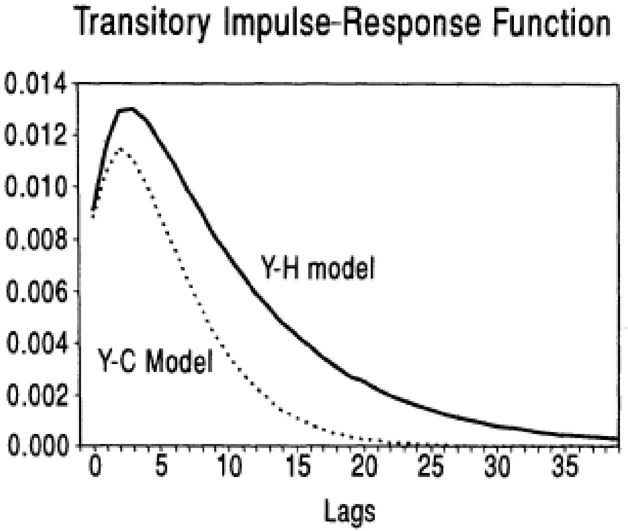
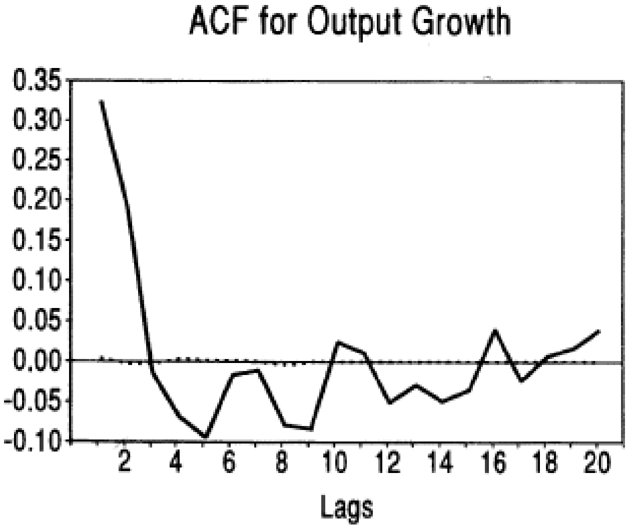
Autocorrelation of output growth rate in the data



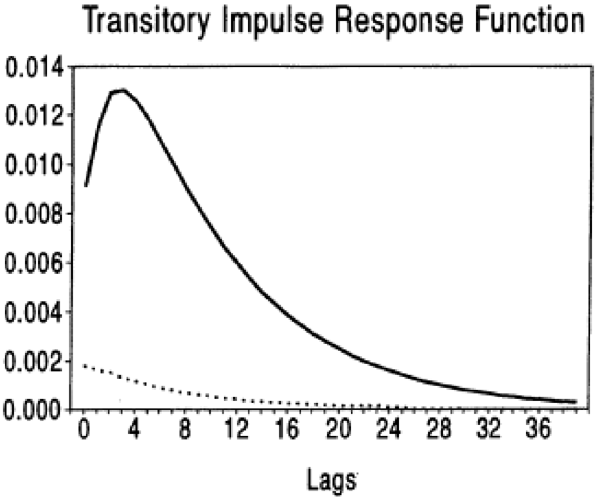
Impulse Response of output to transitory shocks in data



Autocorrelation of output growth rate in the standard RBC model (dotted line)



Impulse Response of output to transitory shocks in the standard RBC model (dotted line)



Labor Market Moments in the data

Tables 1 and 2

Cyclical Properties of U.S. Time Series

Table 1 1955:3–1988:2

Data Series*	Variable j	% S.D. σ_j	Variable vs. Output σ_j/σ_y	Variable vs. Output cor(j,y)	Hours vs. Productivity σ_h/σ_w	Hours vs. Productivity cor(h,w)
Output	y	1.74	1.00	1.00	—	—
Consumption	c	.84	.48	.75	—	—
Investment	i	5.48	3.16	.90	—	—
Labor Market:						
1. Household Survey (All Industries)						
Hours Worked	h	1.42	.82	.87	1.64	.10
Productivity	w	.87	.50	.58		
2. Establishment Survey (Nonag. Industries)						
Hours Worked	h	1.63	.94	.88	1.95	–.13
Productivity	w	.84	.48	.36		
3. Nonag. Industries From Household Survey						
Hours Worked	h	1.75	1.01	.76	1.44	–.35
Productivity	w	1.21	.70	.34		
4. Efficiency Units From Hansen 1991						
Hours Worked	h	1.66	.96	.74	1.37	–.30
Productivity	w	1.22	.70	.41		

Labor Market Moments in the data

Table 2 1947:1–1991:3

Data Series*	Variable j	% S.D. σ_j	Variable vs. Output σ_j/σ_y	Variable vs. Output cor(j,y)	Hours v σ_h/σ_w
Output	y	1.92	1.00	1.00	—
Consumption	c	.86	.45	.71	—
Investment	i	5.33	2.78	.73	—
Labor Market:					
1. Household Survey (All Industries)					
Hours Worked	h	1.50	.78	.82	1.37
Productivity	w	1.10	.57	.63	
2. Establishment Survey (Nonag. Industries)					
Hours Worked	h	1.84	.96	.90	2.15
Productivity	w	.86	.45	.31	

the standard RBC model

- The model

$$v(k_t, A_t) = \max_{c_t, n_t, k_{t+1}} \{\log c_t + \gamma \log(1 - n_t) + \beta E_t v(k_{t+1}, A_{t+1}) + \lambda_t [A_t k_t^{\alpha} n_t^{1-\alpha} + (1-\delta) k_t - c_t - k_{t+1}]\} \quad (1)$$

- the first order condition

$$\frac{1}{c_t} = \lambda_t \quad (2)$$

$$\frac{\gamma}{1 - n_t} = \lambda_t \frac{(1-\alpha) y_t}{n_t} \quad (3)$$

$$\lambda_t = \beta E_t [v_1'(k_{t+1}, A_{t+1})] \quad (4)$$

- Envelop Theory:

$$v_1'(k_t, A_t) = \lambda_t \frac{\alpha y_t}{k_t} + \lambda_t (1-\delta) \quad (5)$$

Performance of the RBC model

Cyclical Properties of U.S. and Model-Generated Time Series

Type of Data or Model	% S.D. of Output σ_y	Variable vs. Output				Hours vs. Productivity	
		Consumption σ_c/σ_y	Investment σ_i/σ_y	Hours σ_h/σ_y	Productivity σ_w/σ_y	σ_h/σ_w	cor(h,w)
U.S. Time Series*							
Output	1.92	.45	2.78	—	—	—	—
Hours Worked:							
1. Household Survey (All Industries)	—	—	—	.78	.57	1.37	.07
2. Establishment Survey (Nonag. Industries)	—	—	—	.96	.45	2.15	–.14
Models**							
Standard	1.30	.31	3.15	.49	.53	.94	.93
Nonseparable Leisure	1.51	.29	3.23	.65	.40	1.63	.80

Performance of the RBC model

- RBC fails in explaining both labor market volatility, and the correlation between wage and hours.
- RBC fails in explaining output persistence.

Indivisible Labor

- A family has a continuum of member. The family period-by-period utility function is

$$U_t = \int [u(c_t(i)) + \phi(n_t(i))] \, di \qquad (6)$$

- Where $n_t(i) = 0$,or 1. $n_t(i) = 1$ implies member i is working. Denote n_t as the total number of members who is working.
- we assume $\phi(1) < \phi(0)$. The total constraint is

$$\int c_t(i) di + k_{t+1} = A_t k_t^{\alpha} n_t^{1-\alpha} + (1-\delta) k_t \qquad (7)$$

Indivisible Labor

- The total utility from leisure is

$$n_t\phi(1) + (1 - n_t)\phi(0) = \phi(0) - [\phi(0) - \phi(1)]n_t \tag{8}$$

- which is propotional to n_t. Since symmetry across $c_t(i)$, we must have $c_t(i)$ are the same across i, or $c_t(i) = c_t$, so the utility function is

$$U_t = u(c_t) - a_L n_t \tag{9}$$

  where $a_L = \phi(0) - \phi(1)$

- The constraint is then given by

$$c_t + k_{t+1} = A_t k_t^{\alpha} n_t^{1-\alpha} + (1 - \delta)k_t \tag{10}$$

Indivisible Labor-F.O.Cs

- Set up the Bellman equation as

$$\begin{aligned} v(k_t, A_t) &= \max\{u(c_t) - a_L n_t + \beta E_t v(k_{t+1}, A_{t+1}) \\ &\quad + \lambda_t [A_t k_t^{\alpha} n_t^{1-\alpha} + (1-\delta)k_t - c_t - k_{t+1}]\} \end{aligned} \tag{11}$$

- F.O.Cs

$$u'(c_t) = \lambda_t \tag{12}$$

$$a_L = \lambda_t \frac{(1-\alpha)y_t}{n_t} \tag{13}$$

$$\lambda_t = \beta E_t[v_1'(k_{t+1}, A_{t+1})] \tag{14}$$

- Envelop Theory:

$$v_1'(k_t, A_t) = \lambda_t \frac{\alpha y_t}{k_t} + (1-\delta)\lambda_t \tag{15}$$

Indivisible Labor-F.O.Cs

- The F.O.Cs become

$$a_L = \frac{1}{c_t}\frac{(1-\alpha)y_t}{n_t} \tag{16}$$

$$\frac{1}{c_t} = \beta E_t \frac{1}{c_{t+1}}[\frac{\alpha y_{t+1}}{k_{t+1}} + (1-\delta)] \tag{17}$$

$$c_t + k_{t+1} = y_t + (1-\delta)k_t \tag{18}$$

where

$$y_t = A_t k_t^{\alpha} n_t^{1-\alpha}$$

- Transversaility condition:

$$E_0 \lim_{t\to\infty} \beta^t v_1'(k_t, A_t)k_t = 0 \tag{19}$$

Indivisible Labor-Steady-State

- Assume in the steady-state $A = 1$, We have in the steady-state,

$$y_k = \frac{y}{k} = \frac{\beta^{-1} - (1-\delta)}{\alpha} \tag{20}$$

$$c_k = y_K - \delta \tag{21}$$

$$n = \frac{(1-\alpha)y_k}{c_k}\frac{1}{a_L} \tag{22}$$

$$y = k^{\alpha} n^{1-\alpha} = (\frac{y}{y_k})^{\alpha} n^{1-\alpha} \tag{23}$$

- or

$$y = \left(\frac{1}{y_k}\right)^{\frac{\alpha}{1-\alpha}} n; k = y/y_k; c = c_k k \tag{24}$$

Indivisible Labor-Steady-State

- Assume in the steady-state $A = 1$, We have in the steady-state,

$$y_k = \frac{y}{k} = \frac{\beta^{-1} - (1-\delta)}{\alpha} \tag{25}$$

$$c_k = y_K - \delta \tag{26}$$

$$n = \frac{(1-\alpha)y_k}{c_k}\frac{1}{a_L} \tag{27}$$

$$y = k^{\alpha} n^{1-\alpha} = (\frac{y}{y_k})^{\alpha} n^{1-\alpha} \tag{28}$$

- or

$$y = \left(\frac{1}{y_k}\right)^{\frac{\alpha}{1-\alpha}} n; k = y/y_k; c = c_k k \tag{29}$$

Indivisible Labor-log-linearizing

- The log-linearized f.o.cs are

$$\hat{y}_t - \hat{n}_t - \hat{c}_t = 0 \tag{30}$$

$$-\hat{c}_t = -E_t\hat{c}_{t+1} + [1 - \beta(1-\delta)]\, E_t(\hat{y}_{t+1} - \hat{k}_{t+1}) \tag{31}$$

$$\hat{k}_{t+1} = y_k\hat{y}_t - c_k\hat{c}_t + (1-\delta)\hat{k}_t \tag{32}$$

$$\hat{y}_t = \hat{A}_t + \alpha\hat{k}_t + (1-\alpha)\hat{n}_t \tag{33}$$

- And assume technology shocks follows

$$\hat{A}_t = \rho\hat{A}_{t-1} + \varepsilon_t \tag{34}$$

- Homework 1: solving the above indivisible labor model and show it can increase hours' volatility

Habit Formation Model

- Now consider the persistence problem. We add habit formation and adjustment costs one by one into the model.
- Assume the utility function becomes

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\log(c_t - hc_{t-1}) - a_L n_t\right] \tag{35}$$

- the period-by-period constraint is still the same

$$c_t + k_{t+1} = A_t k_t^{\alpha} n_t^{1-\alpha} + (1-\delta) k_t \tag{36}$$

Habit Formation Model-Bellman Equation

- We first set up the bellman equations. In each period t, c_{t-1}, k_t, A_t are states variables , so we set up the Bellman Equations as

$$\begin{aligned} V(c_{t-1}, k_t, A_t) &= \max\{\log(c_t - hc_{t-1}) - a_L n_t \\ &\quad + \beta E_t V(c_t, k_{t+1}, A_{t+1}) \\ &\quad + \lambda_t [A_t k_t^{\alpha} n_t^{1-\alpha} + (1-\delta)k_t - c_t - k_{t+1}\} \end{aligned} \tag{37}$$

- first order condtion with respect to c_t :

$$\frac{1}{c_t - hc_{t-1}} + \beta E_t V_c'(c_t, k_{t+1}, A_{t+1}) = \lambda_t \tag{38}$$

Habit Formation Model-Bellman Equation

- first order condtion with respect to n_t :

$$\lambda_t \frac{(1-\alpha)y_t}{n_t} = a_L \tag{39}$$

- first order condtion with respect to k_{t+1} :

$$\lambda_t = \beta E_t[V_k'(c_t, k_{t+1}, A_{t+1})] \tag{40}$$

- Envelop Theory

$$V_c'(c_{t-1}, k_t, A_t) = -\frac{h}{c_t - hc_{t-1}} \tag{41}$$

$$V_k'(c_{t-1}, k_t, A_t) = \lambda_t[\frac{\alpha y_t}{k_t} + (1-\delta)] \tag{42}$$

Habit Formation Model-Bellman Equation

- So the first order conditions are be summarized by

$$\lambda_t = \frac{1}{c_t - hc_{t-1}} - \beta h E_t \frac{1}{c_{t+1} - hc_t} \tag{43}$$

$$\lambda_t \frac{(1-\alpha)y_t}{n_t} = a_L \tag{44}$$

$$\lambda_t = \beta E_t \lambda_{t+1} [\frac{\alpha y_{t+1}}{k_{t+1}} + (1-\delta)] \tag{45}$$

$$A_t k_t^{\alpha} n_t^{1-\alpha} + (1-\delta)k_t = c_t + k_{t+1} \tag{46}$$

- where output is defined as

$$y_t = A_t k_t^{\alpha} n_t^{1-\alpha} \tag{47}$$

Habit Formation Model-Steady-State

- Notice that the steady-state

$$y_k = \frac{\beta^{-1} - 1 + \delta}{\alpha}; c_k = y_k - \delta \tag{48}$$

is the same as before.

- and output is

$$y = (\frac{1}{y_k})^{\frac{\alpha}{1-\alpha}} n \tag{49}$$

- we need to determine n, in the steady-state

$$\frac{1 - \beta h}{(1-h)} \frac{1}{c} \frac{(1-\alpha) y}{n} = a_L \tag{50}$$

- or

$$n = \frac{1 - \beta h}{(1-h)} \frac{1}{c_k} \frac{(1-\alpha) y_k}{a_L} \tag{51}$$

Habit-Log-linearized equations

- The log-linearized equations

$$\hat{\lambda}_t = -\frac{1+\beta h^2}{(1-\beta h)(1-h)}\hat{c}_t + \frac{h}{(1-\beta h)(1-h)}\hat{c}_{t-1} + \frac{\beta h}{(1-\beta h)(1-h)}E_t\hat{c}_{t+1} \tag{52}$$

$$\hat{\lambda}_t + \hat{y}_t - \hat{n}_t = 0 \tag{53}$$

$$\hat{\lambda}_t = E_t\hat{\lambda}_{t+1} + (1-\beta(1-\delta))E_t[\hat{y}_{t+1} - \hat{k}_{t+1}] \tag{54}$$

$$\hat{k}_{t+1} = y_k\hat{k}_t + (1-\delta)\hat{k}_t - c_k\hat{c}_t \tag{55}$$

$$\hat{y}_t = \hat{A}_t + \alpha\hat{k}_t + (1-\alpha)\hat{n}_t \tag{56}$$

$$\hat{A}_t = \rho\hat{A}_{t-1} + \varepsilon_t \tag{57}$$

Model setup-Assumption

- In the previous model, the capital accumulates according to

$$k_{t+1} = (1-\delta)k_t + i_t \tag{58}$$

- where i_t is the investment, we can also write the resource constraint as

$$c_t + i_t = y_t \tag{59}$$

- Now consider there is capital adjustment cost such that

$$k_{t+1} = (1-\delta)k_t + \varphi(\frac{i_t}{k_t})k_t \tag{60}$$

- φ is concave with $\varphi(\delta) = \delta$ and $\varphi'(\delta) = 1$.

Model setup-Bellman Equation

- There are $c_t, k_t, A_t,$, three state variables
- There are two constraints

$$c_t + i_t = y_t \tag{61}$$

$$k_{t+1} = (1-\delta)k_t + \varphi(\frac{i_t}{k_t})k_t \tag{62}$$

- Denote λ_t, χ_t are the Lagrangian mutlipliers of the above two constraints. Denote $q_t = \frac{\chi_t}{\lambda_t}$,

Model setup-Bellman Equation

- So we set up the Bellman Equations as

$$\begin{aligned} V(c_{t-1}, k_t, A_t) \quad = \quad & \max_{c_t, n_t, i_t, k_{t+1}} \{\log(c_t - hc_{t-1}) - a_L n_t \\ & +\beta E_t V(c_t, k_{t+1}, A_{t+1}) \\ & +\lambda_t [A_t k_t^{\alpha} n_t^{1-\alpha} - c_t - i_t] \\ & +\lambda_t q_t [(1-\delta) k_t + \varphi(\frac{i_t}{k_t}) k_t - k_{t+1}]\} \end{aligned} \tag{63}$$

Model setup-FOCs

- first order condtion with respect to c_t :

$$\frac{1}{c_t - hc_{t-1}} + \beta E_t V_c'(c_t, k_{t+1}, A_{t+1}) = \lambda_t \tag{64}$$

- first order condtion with respect to n_t :

$$\lambda_t \frac{(1-\alpha)y_t}{n_t} = a_L \tag{65}$$

- first order condtion with respect to i_t :

$$\lambda_t = \lambda_t q_t \varphi'(\frac{i_t}{k_t}) \tag{66}$$

Model setup-FOCs

- first order condtion with respect to k_{t+1} :

$$\lambda_t q_t = \beta E_t V_k'(c_t, k_{t+1}, A_{t+1}) \tag{67}$$

- Envelop Theory

$$V_c'(c_{t-1}, k_t, A_t) = -\frac{h}{c_t - hc_{t-1}} \tag{68}$$

$$V_k'(c_{t-1}, k_t, A_t) = \lambda_t \frac{\alpha y_t}{k_t} + \lambda_t q_t [(1-\delta) + \varphi(\frac{i_t}{k_t}) - \varphi'(\frac{i_t}{k_t})\frac{i_t}{k_t}] \tag{69}$$

Model setup-FOCs

- So the first order conditions are be summarized by

$$\lambda_t = \frac{1}{c_t - hc_{t-1}} - \beta h E_t \frac{1}{c_{t+1} - hc_t} \quad (70)$$

$$\lambda_t \frac{(1-\alpha) y_t}{n_t} = a_L \quad (71)$$

$$q_t = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \{ \frac{\alpha y_{t+1}}{k_{t+1}} + q_{t+1} [(1-\delta) + \varphi(\frac{i_{t+1}}{k_{t+1}}) - \varphi'(\frac{i_{t+1}}{k_{t+1}}) \frac{i_{t+1}}{k_{t+1}}] \} \quad (72)$$

$$1 = q_t \varphi'(\frac{i_t}{k_t}) \quad (73)$$

$$y_t = A_t k_t^{\alpha} n_t^{1-\alpha} = c_t + i_t \quad (74)$$

- and capital follows

$$k_{t+1} = (1-\delta) k_t + \varphi(\frac{i_t}{k_t}) k_t \quad (75)$$

Model setup-FOCs

- Equations

$$1 = q_t \varphi'(\frac{i_t}{k_t}) \tag{76}$$

says that investment rate should be determined by q_t alone. So q_t is a very important economic variable.

- what is q_t? Notice $\lambda_t = \frac{\partial V_t}{\partial y_t}$, namely one dollar increase in income leads to λ_t unit increase in utility
- by $\frac{\partial V_t}{\partial k_{t+1}} = \lambda_t q_t$, an increase in one unit of installed capital increase the utility by $\lambda_t q_t$
- so an unit installed capital is equivalent to q_t unit dollars.

Model setup-Steady-State

- We now study the steady-state of the above model. By assumption $\varphi(\delta) = \delta$ and $\varphi'(\delta) = 1$. We must have

$$\frac{i}{k} = \delta; q = 1 \tag{77}$$

- So we have

$$1 = \beta\{\frac{\alpha y}{k} + [(1-\delta) + \varphi(\delta) - \varphi'(\delta)\delta]\} \tag{78}$$

$$y_k = \frac{\beta^{-1} - 1 + \delta}{\alpha}; c_k = y_k - \delta \tag{79}$$

is the same as before.

- The rest variables are the same as the model without adjustment cost.

Model setup-log-linearization

A few equations require additonal attention

- marginal utility

$$\hat{\lambda}_t = -\frac{1+\beta h^2}{(1-\beta h)(1-h)}\hat{c}_t + \frac{h}{(1-\beta h)(1-h)}\hat{c}_{t-1} + \frac{\beta h}{(1-\beta h)(1-h)}E_t\hat{c}_{t+1} \quad (80)$$

- capital accumuation, defining $\varphi(\frac{i_t}{k_t}) = \varphi_t$, we have

$$\hat{k}_{t+1} = (1-\delta)k_t + \delta[\hat{\varphi}_t + \hat{k}_t] \quad (81)$$

$$\hat{\varphi}_t = \frac{\varphi'(\delta)}{\varphi(\delta)}[\frac{di_t k - idk_t}{k^2}] = \frac{1}{\delta}[\frac{i}{k}\frac{di_t}{i} - \frac{i}{k}\frac{dk_t}{k}] = \hat{\imath}_t - \hat{k}_t \rightarrow \quad (82)$$

$$\hat{k}_{t+1} = (1-\delta)k_t + \delta\hat{\imath}_t \quad (83)$$

A few equations require additonal attention

- Investment Rate :$1 = q_t \varphi'(\frac{i_t}{k_t})$

$$
\begin{aligned}
0 &= \hat{q}_t + \frac{\varphi''(\frac{i}{k})}{\varphi'(\frac{i}{k})}\left[\frac{di_t k - idk_t}{k^2}\right] \\
&= \hat{q}_t + \delta\varphi''(\delta)[\hat{\imath}_t - \hat{k}_t] \qquad (84)
\end{aligned}
$$

- q_t is the most difficult equation

$$
q_t = \beta E_t \frac{\lambda_{t+1}}{\lambda_t}\{\frac{\alpha y_{t+1}}{k_{t+1}} + q_{t+1}[(1-\delta) + \varphi(\frac{i_{t+1}}{k_{t+1}}) - \varphi'(\frac{i_{t+1}}{k_{t+1}})\frac{i_{t+1}}{k_{t+1}}]\} \rightarrow
$$

so derive its linearized equation in several step

- step 1,Define

$$
\begin{aligned}
\frac{\alpha y_{t+1}}{k_{t+1}} + q_{t+1}[(1-\delta) + \varphi(\frac{i_{t+1}}{k_{t+1}}) - \varphi'(\frac{i_{t+1}}{k_{t+1}})\frac{i_{t+1}}{k_{t+1}}] &= z_{t+1} \qquad (85) \\
z &= \frac{1}{\beta}
\end{aligned}
$$

Model setup-log-linearization

- by step 1, so we have

$$\hat{q}_t + \hat{\lambda}_t = E_t(\hat{z}_{t+1} + \hat{\lambda}_{t+1}) \tag{86}$$

- step 2, defining

$$\begin{aligned} \frac{\alpha y_{t+1}}{k_{t+1}} &= z_{1t+1}, \\ q_{t+1}[(1-\delta) + \varphi(\frac{i_{t+1}}{k_{t+1}}) - \varphi'(\frac{i_{t+1}}{k_{t+1}})\frac{i_{t+1}}{k_{t+1}}] &= z_{2t+1} \end{aligned}$$

so we have

$$\hat{z}_{t+1} = \frac{z_1}{z}\hat{z}_{1t+1} + \frac{z_2}{z}\hat{z}_{2t+1} = [1-\beta(1-\delta)]\hat{z}_{1t+1} + \beta(1-\delta)\hat{z}_{2t+1} \tag{87}$$

Model setup-log-linearization

- by step 2 , we have

$$\hat{z}_{1t+1} = \hat{y}_{t+1} - \hat{k}_{t+1} \tag{88}$$

- we need to determine $\hat{z}_{2t+1}$, by definition

$$z_{2t+1} = q_{t+1}[(1-\delta) + \varphi(\frac{i_{t+1}}{k_{t+1}}) - \varphi'(\frac{i_{t+1}}{k_{t+1}})\frac{i_{t+1}}{k_{t+1}}] \tag{89}$$

- so we have

$$\begin{aligned} \hat{z}_{2t+1} \quad &= \quad \hat{q}_{t+1} + \frac{1}{(1-\delta) + \varphi(\frac{i}{k}) - \varphi'(\frac{i}{k})\frac{i}{k}} \times \\ &\{\varphi'(\frac{i}{k})[\frac{di_{t+1}k - idk_{t+1}}{k^2}] - \varphi'(\frac{i}{k})[\frac{di_{t+1}k - idk_{t+1}}{k^2}] \\ &-\frac{i}{k}\varphi''(\frac{i}{k})[\frac{di_{t+1}k - idk_{t+1}}{k^2}]\} \end{aligned} \tag{90}$$

Model setup-log-linearization

- Or we have

$$\hat{z}_{2t+1} = \hat{q}_{t+1} + \frac{\delta^2 \varphi''(\delta)}{1-\delta}[\hat{\imath}_{t+1} - \hat{k}_{t+1}] \tag{91}$$

- so we have

$$\begin{aligned} \hat{q}_t + \hat{\lambda}_t &= E_t(\hat{z}_{t+1} + \hat{\lambda}_{t+1}) \\ &= E_t\hat{\lambda}_{t+1} + [1-\beta(1-\delta)]E_t[\hat{y}_{t+1} - \hat{k}_{t+1}] \\ &\quad +\beta(1-\delta)\{\hat{q}_{t+1} + \frac{\delta^2\varphi''(\delta)}{1-\delta}[\hat{\imath}_{t+1} - \hat{k}_{t+1}]\} \end{aligned} \tag{92}$$

- Notice by $\hat{q}_t + \delta\varphi''(\delta)[\hat{\imath}_t - \hat{k}_t] = 0$, we have

$$\frac{\delta^2\varphi''(\delta)}{1-\delta}[\hat{\imath}_{t+1} - \hat{k}_{t+1}] = -\frac{\delta}{1-\delta}\hat{q}_{t+1} \tag{93}$$

- so we have ,

$$\hat{q}_t + \hat{\lambda}_t = E_t\hat{\lambda}_{t+1} + [1-\beta(1-\delta)]E_t[\hat{y}_{t+1} - \hat{k}_{t+1}] + \beta E_t\hat{q}_{t+1} \tag{94}$$