



LINEAR APPROXIMATION OF THE BASELINE RBC MODEL

JANUARY 8, 2020

LINEARIZATION

- For $f(x, y, z) = 0$, multivariable Taylor linear expansion around $(\bar{x}, \bar{y}, \bar{z})$

$$f(x, y, z) \approx f(\bar{x}, \bar{y}, \bar{z}) + f_x(\bar{x}, \bar{y}, \bar{z})(x - \bar{x}) + f_y(\bar{x}, \bar{y}, \bar{z})(y - \bar{y}) + f_z(\bar{x}, \bar{y}, \bar{z})(z - \bar{z})$$

(Illustrative example
in scalars)

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- Four equations describe the dynamic solution to RBC model

(Illustrative example
in scalars)

- Consumption-leisure efficiency condition

$$-\frac{u_n(c_t, n_t)}{u_c(c_t, n_t)} = z_t m_n(k_t, n_t)$$

- Consumption-investment efficiency condition

$$u_c(c_t, n_t) = \beta E_t \left[u_c(c_{t+1}, n_{t+1}) (1 - \delta + z_{t+1} m_k(k_{t+1}, n_{t+1})) \right]$$

- Aggregate resource constraint

$$c_t + k_{t+1} - (1 - \delta)k_t = z_t m(k_t, n_t)$$

- Law of motion for TFP

$$\ln z_{t+1} = (1 - \rho_z) \ln \bar{z} + \rho_z \ln z_t + \varepsilon_{t+1}^z$$

STEADY STATE

- **Deterministic** steady state the natural local point of approximation
- Shut down all shocks and set exogenous variables at their means
- **The Idea:** Let economy run for many (infinite) periods
 - Time eventually “doesn’t matter” any more
 - Drop all time indices

$$-\frac{u_n(\bar{c}, \bar{n})}{u_c(\bar{c}, \bar{n})} = \bar{z}m_n(\bar{k}, \bar{n})$$

$$u_c(\bar{c}, \bar{n}) = \beta u_c(\bar{c}, \bar{n}) [m_k(\bar{k}, \bar{n}) + 1 - \delta]$$

$$\bar{c} + \delta\bar{k} = \bar{z}m(\bar{k}, \bar{n})$$

$$\ln \bar{z} = (1 - \rho_z) \ln \bar{z} + \rho_z \ln \bar{z} \Rightarrow \bar{z} = \bar{z} \quad (\text{a parameter of the model})$$

- Given functional forms and parameter values, solve for (c, n, k)
 - **The steady state of the model**
 - **Taylor expansion around this point**

LINEARIZATION ALGORITHMS

- **Schmitt-Grohe and Uribe (2004 *JEDC*)**
 - A **perturbation** algorithm
 - A class of methods used to find an **approximate** solution to a problem that cannot be solved exactly, **by starting from the exact solution of a related problem**
 - Applicable if the problem can be formulated by adding a “small” term to the description of the exactly-solvable problem
 - (Matlab code available through Columbia Dept. of Economics web site – **DO NOT USE IN THIS CLASS**)

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- **Uhlig (1999, chapter in *Computational Methods for the Study of Dynamic Economies*)**
 - Uses a generalized eigen-decomposition
 - Typically implemented with Schur decomposition (Sims algorithm)
 - Matlab code available on [Uhlig's site](#)

LINEARIZATION OF THE RBC MODEL

Define **co-state** vector and **state** vector

$$y_t = \begin{bmatrix} c_t \\ n_t \end{bmatrix} \quad x_t = \begin{bmatrix} k_t \\ z_t \end{bmatrix}$$

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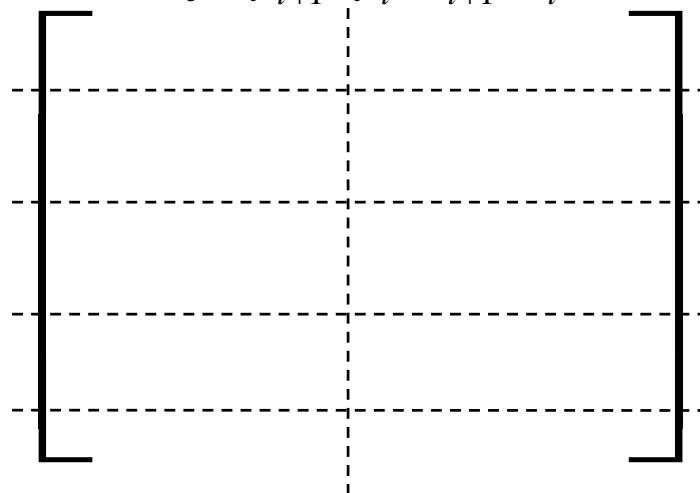
Order model's dynamic equations in a **vector** $\equiv f(y_{t+1}, y_t, x_{t+1}, x_t) = 0$

Consumption-leisure efficiency condition

Consumption-investment efficiency condition

Aggregate resource constraint

Law of motion for TFP



LINEARIZATION OF THE RBC MODEL

Need four **matrices** of derivatives

1. Differentiate $f(y_{t+1}, y_t, x_{t+1}, x_t)$ with respect to (elements of) y_{t+1}

First derivatives with respect to:

	c_{t+1}	n_{t+1}	
Consumption-leisure efficiency condition			
Consumption-investment efficiency condition			
Aggregate resource constraint			
Law of motion for TFP			

$= f_{y_{t+1}}$

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LINEARIZATION OF THE RBC MODEL

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3. Differentiate $f(y_{t+1}, y_t, x_{t+1}, x_t)$ with respect to (elements of) x_{t+1}

First derivatives with respect to:

	k_{t+1}	z_{t+1}	
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Consumption-investment efficiency condition			
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LINEARIZATION OF THE RBC MODEL

Need four **matrices** of derivatives

4. Differentiate $f(y_{t+1}, y_t, x_{t+1}, x_t)$ with respect to (elements of) x_t

First derivatives with respect to:

	k_t	z_t	
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LINEARIZATION OF THE RBC MODEL

The model's dynamic **expectational** equations

$$E_t [f(y_{t+1}, y_t, x_{t+1}, x_t)] = E_t \begin{bmatrix} f^1(y_{t+1}, y_t, x_{t+1}, x_t) \\ f^2(y_{t+1}, y_t, x_{t+1}, x_t) \\ f^3(y_{t+1}, y_t, x_{t+1}, x_t) \\ f^4(y_{t+1}, y_t, x_{t+1}, x_t) \end{bmatrix}$$

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Consumption-leisure efficiency condition
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Conjecture equilibrium decision rules

Note: $g(\cdot)$ and $h(\cdot)$ are time invariant functions!

$$y_t = g(x_t, \sigma)$$

$$x_{t+1} = h(x_t, \sigma) + \eta \sigma \varepsilon_{t+1}$$

“Perturbation parameter”:
governs size of shocks

**Matrix of standard
deviations of state
variables**

LINEARIZATION OF THE RBC MODEL

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Substitute decision rules
into dynamic equations

“Perturbation parameter”:
governs size of shocks

Matrix of standard
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LINEARIZATION OF THE RBC MODEL

The model's dynamic **expectational** equations

$$\begin{aligned} E_t [f(y_{t+1}, y_t, x_{t+1}, x_t)] &= 0 \\ &= E_t [f(g(x_{t+1}, \sigma), g(x_t, \sigma), h(x_t, \sigma) + \eta\sigma\varepsilon_{t+1}, x_t)] \\ &= E_t [f(g(h(x_t, \sigma) + \eta\sigma\varepsilon_{t+1}, \sigma), g(x_t, \sigma), h(x_t, \sigma) + \eta\sigma\varepsilon_{t+1}, x_t)] \\ &\equiv F(x_t, \sigma) \end{aligned}$$

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 \end{aligned}$$



$$F_x(x_t, \sigma) = 0$$

$$F_\sigma(x_t, \sigma) = 0$$

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Using chain rule and
suppressing arguments

$$F_x(x_t, \sigma) =$$

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$$F_x(x_t, \sigma) = f_{y_{t+1}} \cdot g_x \cdot h_x$$

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$$F_x(x_t, \sigma) = f_{y_{t+1}} \cdot g_x \cdot h_x + f_{y_t} \cdot g_x$$

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Using chain rule and
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 F_x(x_t, \sigma) &= f_{y_{t+1}} \cdot g_x \cdot h_x + f_{y_t} \cdot g_x + f_{x_{t+1}} \cdot h_x + f_{x_t} \\
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 &= 0
 \end{aligned}$$

Setting $\sigma = 0$ shuts
down shocks

Holds, in particular, at the **deterministic** steady state $(\bar{x}, 0)$

$$F_x(\bar{x}, 0) = f_{y_{t+1}} \cdot g_x \cdot h_x + f_{y_t} \cdot g_x + f_{x_{t+1}} \cdot h_x + f_{x_t} = 0$$

Each term evaluated at
the steady state – as per
Taylor theorem

LINEARIZATION OF THE RBC MODEL

- A **quadratic** equation in the elements of g_x and h_x evaluated at the steady state

$$F_x(\bar{x}, 0) = f_{y_{t+1}}(\bar{x}, 0) \cdot g_x(\bar{x}, 0) \cdot h_x(\bar{x}, 0) + f_{y_t}(\bar{x}, 0) \cdot g_x(\bar{x}, 0) + f_{x_{t+1}}(\bar{x}, 0) \cdot h_x(\bar{x}, 0) + f_{x_t}(\bar{x}, 0) = 0$$

- Solve numerically for the elements of g_x and h_x (use `fsolve` OR conduct an eigenvalue decomposition in Matlab)

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- First-order approximation is

$$y_t = g(x_t, \sigma) \approx g(\bar{x}, 0) + g_x(\bar{x}, 0)(x_t - \bar{x}) + g_\sigma(\bar{x}, 0)\sigma$$

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- **DONE!!!**

- Now conduct impulse responses, tabulate business cycle moments, write paper

CERTAINTY EQUIVALENCE

- Displayed by a model if decision rules do **not** depend on the standard deviation of exogenous uncertainty – e.g., **PRECAUTIONARY SAVINGS!**
- For **stochastic** problems with **quadratic objective function** and **linear constraints**, the decision rules are identical to those of the nonstochastic problem

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- Here, we have

$$y_t = g(x_t, \sigma) \approx g(\bar{x}, 0) + g_x(\bar{x}, 0)(x_t - \bar{x}) + \cancel{g_\sigma(\bar{x}, 0)}\sigma$$

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- **SGU Theorem 1: $g_\sigma = 0$ and $h_\sigma = 0$**
 - First-order approximated decision rules do not depend on the size of the shocks, which is governed by σ
 - Not the same thing as **“exact CE,”** but refer to it as **CE**

LINEARIZING THE RBC MODEL

- Assume $u(c_t, n_t) = \ln c_t - \psi \ln n_t$ and $m(k_t, n_t) = k_t^\alpha n_t^{1-\alpha}$
- \therefore consumption-leisure efficiency condition is $\frac{\psi c_t}{n_t} - (1 - \alpha) z_t k_t^\alpha n_t^{-\alpha} = 0$

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- Let $f^1(y_{t+1}, y_t, x_{t+1}, x_t) = \frac{\psi c_t}{n_t} - (1 - \alpha) z_t k_t^\alpha n_t^{-\alpha} = 0$ (and recall $y_t = \begin{bmatrix} c_t \\ n_t \end{bmatrix}$ $x_t = \begin{bmatrix} k_t \\ z_t \end{bmatrix}$)

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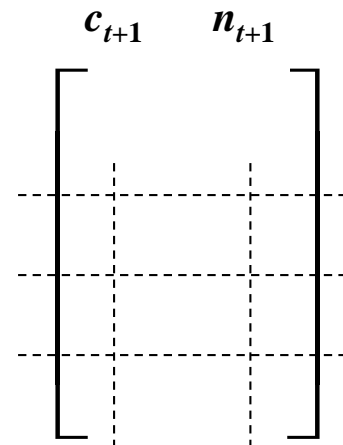
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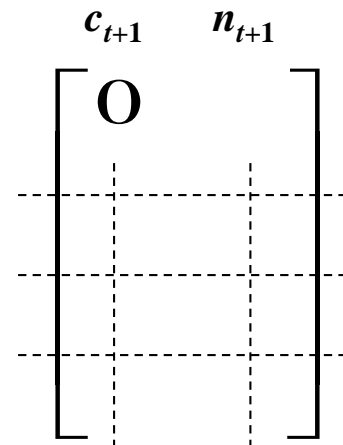
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Law of motion for TFP



LINEARIZING THE RBC MODEL

- Assume $u(c_t, n_t) = \ln c_t - \psi \ln n_t$ and $m(k_t, n_t) = k_t^\alpha n_t^{1-\alpha}$
- \therefore consumption-leisure efficiency condition is $\frac{\psi c_t}{n_t} - (1 - \alpha) z_t k_t^\alpha n_t^{-\alpha} = 0$

- Let $f^1(y_{t+1}, y_t, x_{t+1}, x_t) = \frac{\psi c_t}{n_t} - (1 - \alpha) z_t k_t^\alpha n_t^{-\alpha} = 0$ (and recall $y_t = \begin{bmatrix} c_t \\ n_t \end{bmatrix}$ $x_t = \begin{bmatrix} k_t \\ z_t \end{bmatrix}$)

- Compute first row of matrix $f_{y_{t+1}}$

Consumption-leisure efficiency condition

Consumption-investment efficiency condition

Aggregate resource constraint

Law of motion for TFP

c_{t+1}	n_{t+1}
$\mathbf{0}$	$\mathbf{0}$

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- Compute first row of matrix f_{yt}

c_t	n_t	
Consumption-leisure efficiency condition	$\frac{\psi}{n_t}$	$-\frac{\psi c_t}{n_t^2} + \alpha(1 - \alpha) z_t k_t^\alpha n_t^{-\alpha-1}$
Consumption-investment efficiency condition	-----	-----
Aggregate resource constraint	-----	-----
Law of motion for TFP	-----	-----

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- Compute first row of matrix f_{xt+1}

Consumption-leisure efficiency condition

Consumption-investment efficiency condition

Aggregate resource constraint

Law of motion for TFP

$$\begin{array}{cc}
 & k_{t+1} & z_{t+1} \\
 \left[\begin{array}{cc}
 \mathbf{O} & \mathbf{O} \\
 \vdots & \vdots \\
 \vdots & \vdots \\
 \vdots & \vdots
 \end{array} \right]
 \end{array}$$

LINEARIZING THE RBC MODEL

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- Compute first row of matrix f_{xt}

Consumption-leisure efficiency condition

Consumption-investment efficiency condition

Aggregate resource constraint

Law of motion for TFP

$$\begin{bmatrix} k_t & z_t \\ -\alpha(1 - \alpha) z_t \frac{k_t^{\alpha-1}}{n_t^\alpha} & -(1 - \alpha) k_t^\alpha n_t^{-\alpha} \\ \dots & \dots \\ \dots & \dots \\ \dots & \dots \end{bmatrix}$$

LINEARIZING THE RBC MODEL

- In deterministic steady state, the first rows of $f_{yt+1}, f_{yt}, f_{xt+1}, f_{xt}$ are

$$\begin{array}{rcc}
 f_{yt+1} & 0 & 0 \\
 f_{yt} & \frac{\psi}{\bar{n}} & -\frac{\psi \bar{c}}{\bar{n}^2} + \alpha(1-\alpha)\bar{z}\bar{k}^\alpha \bar{n}^{-\alpha-1} \\
 f_{xt+1} & 0 & 0 \\
 f_{xt} & -\alpha(1-\alpha)\bar{z}\frac{\bar{k}^{\alpha-1}}{\bar{n}^\alpha} & -(1-\alpha)\bar{k}^\alpha \bar{n}^{-\alpha}
 \end{array}$$

LINEARIZING THE RBC MODEL

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$$\begin{array}{rcc}
 f_{yt+1} & 0 & 0 \\
 f_{yt} & \frac{\psi}{\bar{n}} & -\frac{\psi \bar{c}}{\bar{n}^2} + \alpha(1-\alpha)\bar{z}\bar{k}^\alpha \bar{n}^{-\alpha-1} \\
 f_{xt+1} & 0 & 0 \\
 f_{xt} & -\alpha(1-\alpha)\bar{z}\frac{\bar{k}^{\alpha-1}}{\bar{n}^\alpha} & -(1-\alpha)\bar{k}^\alpha \bar{n}^{-\alpha}
 \end{array}$$

- How to compute derivatives $f_{yt+1}, f_{yt}, f_{xt+1}, f_{xt}$?
 - By hand (feasible for small models)
 - Schmitt-Grohe and Uribe Matlab analytical routines
 - Your own Maple or Mathematica programs
 - **MuPad**
 - Dynare package

CALIBRATION? SOLUTION PROCEDURE?

- **Solving for the steady state?**
- **Choosing parameter values?**
- **Next: example code**