LINEAR APPROXIMATION OF THE BASELINE RBC MODEL

SEPTEMBER 17, 2013

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

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

- Four equations describe the dynamic solution to RBC model
 - 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

$$u_{c}(c_{t}, n_{t}) = \beta E_{t} \left[u_{c}(c_{t+1}, n_{t+1}) \left(1 - \delta + z_{t+1} m_{k}(k_{t+1}, n_{t+1}) \right) \right]$$

Aggregate resource constraint

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

Law of motion for TFP

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

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

$$-\frac{u_n(\overline{c},\overline{n})}{u_c(\overline{c},\overline{n})} = \overline{z}m_n(\overline{k},\overline{n})$$
$$u_c(\overline{c},\overline{n}) = \beta u_c(\overline{c},\overline{n}) \Big[m_k(\overline{k},\overline{n}) + 1 - \delta \Big]$$
$$\overline{c} + \delta \overline{k} = \overline{z}m(\overline{k},\overline{n})$$

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

- 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
- 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 at

http://www2.wiwi.hu-berlin.de/institute/wpol/html/toolkit.htm

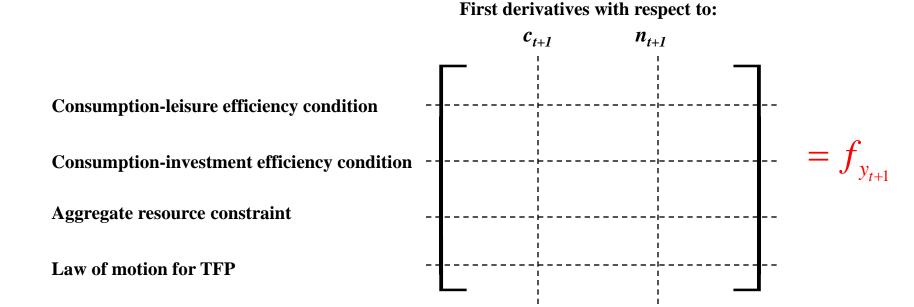
Define <u>co-state</u> vector and <u>state</u> vector

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

<u>Order model's dynamic equations in a vector</u> $\equiv f(y_{t+1}, y_t, x_{t+1}, x_t) = 0$		
Consumption-leisure efficiency condition -		
Consumption-investment efficiency condition -		
Aggregate resource constraint -		
Law of motion for TFP -		

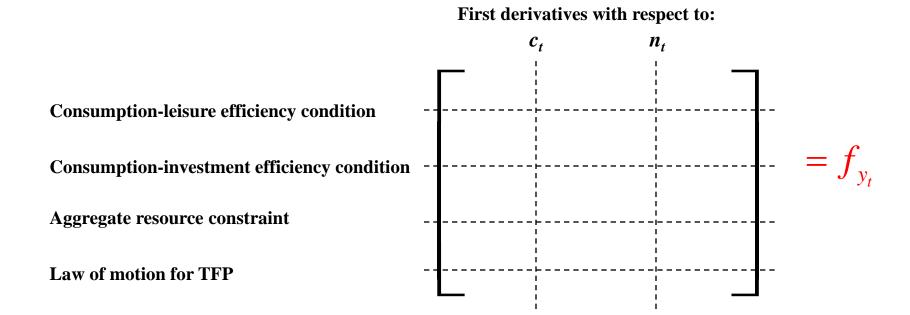
Need four matrices of derivatives

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



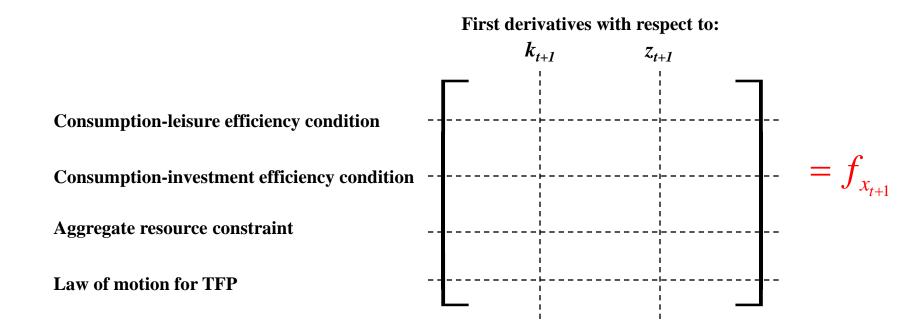
Need four matrices of derivatives

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



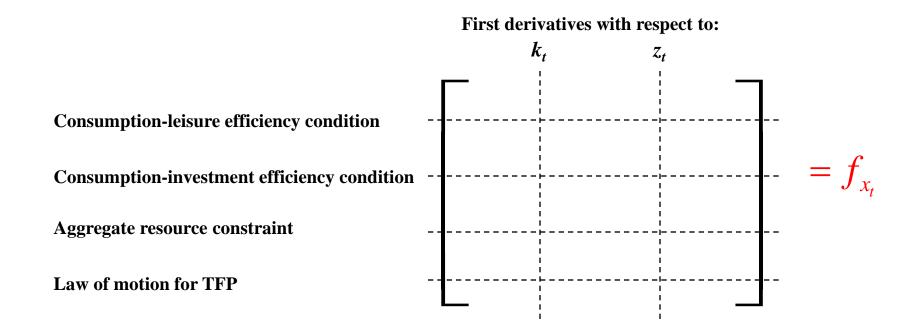
Need four matrices of derivatives

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



<u>Need four matrices of derivatives</u>

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



The model's dynamic expectational equations

$$E_{t}\left[f(y_{t+1}, y_{t}, x_{t+1}, x_{t})\right] = E_{t} \begin{vmatrix} f^{*}(y_{t+1}, y_{t}, x_{t+1}, x_{t}) \\ f^{2}(y_{t+1}, y_{t}, x_{t+1}, x_{t}) \\ f^{3}(y_{t+1}, y_{t}, x_{t+1}, x_{t}) \\ f^{4}(y_{t+1}, y_{t}, x_{t+1}, x_{t}) \end{vmatrix}$$

Consumption-leisure efficiency condition Consumption-investment efficiency condition Aggregate resource constraint Law of motion for TFP

Conjecture equilibrium decision rules

Note: g(.) and h(.) are time invariant functions!

$$y_{t} = g(x_{t}, \sigma)$$

$$x_{t+1} = h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}$$
Substitute decision rules
into dynamic equations
$$Matrix \text{ of standard} \\ deviations \text{ of state} \\ variables$$

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The model's dynamic expectational equations

$$E_{t}[f(y_{t+1}, y_{t}, x_{t+1}, x_{t})] = 0$$

$$= E_{t}[f(g(x_{t+1}, \sigma), g(x_{t}, \sigma), h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}, x_{t}]]$$

$$= E_{t}[f(g(h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}, \sigma), g(x_{t}, \sigma), h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}, x_{t}]]$$

$$\equiv F(x_{t}, \sigma)$$

$$\bigcup$$

$$F_{x}(x_{t}, \sigma) = 0$$

$$F_{\sigma}(x_{t}, \sigma) = 0$$

The model's dynamic expectational equations

$$E_{t}[f(y_{t+1}, y_{t}, x_{t+1}, x_{t})] = 0$$

= $E_{t}[f(g(x_{t+1}, \sigma), g(x_{t}, \sigma), h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}, x_{t}]$
= $E_{t}[f(g(h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}, \sigma), g(x_{t}, \sigma), h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}, x_{t}]$
= $F(x_{t}, \sigma)$

Using chain rule and suppressing arguments

 $F_x(x_t,\sigma) =$

The model's dynamic expectational equations

$$E_{t}[f(y_{t+1}, y_{t}, x_{t+1}, x_{t})] = 0$$

$$= E_{t}[f(g(x_{t+1}, \sigma), g(x_{t}, \sigma), h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}, x_{t}]]$$

$$= E_{t}[f(g(h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}, \sigma), g(x_{t}, \sigma), h(x_{t}, \sigma) + \eta \sigma \varepsilon_{t+1}, x_{t}]]$$

$$\equiv F(x_{t}, \sigma)$$

$$\bigcup$$
Using chain rule and suppressing arguments
$$F_{x}(x_{t}, \sigma) = f_{y_{t+1}} \cdot g_{x} \cdot h_{x} + f_{y_{t}} \cdot g_{x} + f_{x_{t+1}} \cdot h_{x} + f_{x_{t}}$$

$$= 0$$
Holds, in particular, at the deterministic steady state ($\overline{x}, 0$)
$$E_{t}(\overline{x}, 0) = f_{x_{t+1}} \cdot g_{x_{t}} + f_{x_{t}} +$$

 $F_{x}(\overline{x},0) = f_{y_{t+1}} \cdot g_{x} \cdot h_{x} + f_{y_{t}} \cdot g_{x} + f_{x_{t+1}} \cdot h_{x} + f_{x} = 0 \qquad \text{the steady state - just as} \\ \text{Taylor theorem requires}$

• A quadratic equation in the elements of g_x and h_x evaluated at the steady state $F_x(\overline{x},0) = f_{y_{x+1}}(\overline{x},0) \cdot g_x(\overline{x},0) \cdot h_x(\overline{x},0) + f_{y_x}(\overline{x},0) \cdot g_x(\overline{x},0) + f_{x_{x+1}}(\overline{x},0) \cdot h_x(\overline{x},0) + f_{y_x}(\overline{x},0) = 0$

• Solve numerically for the elements of g_x and h_x (use fsolve in Matlab)

Recall conjectured equilibrium decision rules

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

First-order approximation is

$$y_{t} = g(x_{t}, \sigma) \approx g(\overline{x}, 0) + g_{x}(\overline{x}, 0)(x_{t} - \overline{x}) + g_{\sigma}(\overline{x}, 0)\sigma \quad \text{SGU Theorem 1:}$$

$$x_{t+1} = h(x_{t}, \sigma) \approx h(\overline{x}, 0) + h_{x}(\overline{x}, 0)(x_{t} - \overline{x}) + h_{\sigma}(\overline{x}, 0)\sigma \quad g_{\sigma} = 0 \text{ and } h_{\sigma} = 0$$

$$= 0$$

= 0

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
 - Here, we have $y_{t} = g(x_{t}, \sigma) \approx g(\overline{x}, 0) + g_{x}(\overline{x}, 0)(x_{t} - \overline{x}) + g_{\sigma}^{\uparrow}(\overline{x}, 0)\sigma$ $x_{t+1} = h(x_{t}, \sigma) \approx h(\overline{x}, 0) + h_{x}(\overline{x}, 0)(x_{t} - \overline{x}) + h_{\sigma}(\overline{x}, 0)\sigma$
- 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

= 0

• Not the same thing as "exact CE," but refer to it as CE

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

- Assume $u(c_t, n_t) = \ln c_t \psi \ln n_t$ and $m(k_t, n_t) = k_t^{\alpha} n_t^{1-\alpha}$
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 • Compute first row of matrix f_{yt+1} c_{t+1} n_{t+1}

 Consumption-leisure efficiency condition
 c_{t+1} n_{t+1}

 Consumption-leisure efficiency condition
 c_{t+1} n_{t+1}

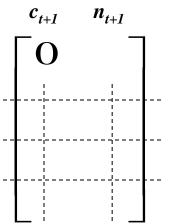
 Aggregate resource constraint
 c_{t+1} c_{t+1}

 Law of motion for TFP
 c_{t+1} c_{t+1}

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

• 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_{vt+1} C_{t+1} **Consumption-leisure efficiency condition Consumption-investment efficiency condition** Aggregate resource constraint Law of motion for TFP



- 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_{yt+1} c_{t+1} n_{t+1}

 Consumption-leisure efficiency condition
 O O

 Consumption-investment efficiency condition
 O O

 Aggregate resource constraint
 O O

 Law of motion for TFP
 O O

- 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_{yt} c_t n_t Consumption-leisure efficiency condition Consumption-investment efficiency condition Aggregate resource constraint Law of motion for TFP

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

 Z_{t+1}

- 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_{xt}

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

k.

 Z_t

- 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_{xt} Consumption-leisure efficiency condition Consumption-investment efficiency condition Aggregate resource constraint Law of motion for TFP • Compute first row of matrix f_{xt} $-\alpha(1-\alpha)z_t \frac{k_t^{\alpha-1}}{n_t^{\alpha}} -(1-\alpha)\frac{k_t^{\alpha}}{n_t^{\alpha+1}}$

• In deterministic steady state, the first rows of $f_{yt+1}, f_{yt}, f_{xt+1}, f_{xt}$ are f_{yt+1} 0 0 0

$$f_{yt} \qquad \frac{\psi}{\overline{n}} \qquad -\frac{\psi c}{\overline{n}^2} + \alpha (1-\alpha) \overline{z} \overline{k}^{\alpha} \overline{n}^{-\alpha-1}$$

$$f_{xt+1} \qquad 0 \qquad 0$$

$$f_{xt} \qquad -\alpha (1-\alpha) \overline{z} \frac{\overline{k}^{\alpha-1}}{\overline{n}^{\alpha}} \qquad -(1-\alpha) \frac{\overline{k}^{\alpha}}{\overline{n}^{\alpha+1}}$$

0

- In deterministic steady state, the first rows of $f_{yt+1}, f_{yt}, f_{xt+1}, f_{xt}$ are
 - $f_{yt} \qquad \frac{\psi}{\overline{n}} \qquad -\frac{\psi\overline{c}}{\overline{n}^2} + \alpha(1-\alpha)\overline{z}\overline{k}^{\alpha}\overline{n}^{-\alpha-1}$ $f_{xt+1} \qquad 0 \qquad 0$

$$f_{xt} \qquad -\alpha(1-\alpha)\overline{z}\frac{\overline{k}^{\alpha-1}}{\overline{n}^{\alpha}} \qquad -(1-\alpha)\frac{\overline{k}^{\alpha}}{\overline{n}^{\alpha+1}}$$

• How to compute derivatives f_{yt+1} , f_{yt} , f_{xt+1} , f_{xt} ?

- By hand (feasible for small models)
- Schmitt-Grohe and Uribe (or your own!) Matlab analytical/symbolic routines

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- Your own Maple or Mathematica programs
- Dynare package

 f_{yt+1}

CALIBRATION?

Solving for the steady state?

Choosing parameter values?

Next: calibration of the baseline representative-agent (RBC + growth) model